SPECIAL COLLECTOR'S EDITION

SCIENTIFIC AMERICAN

CLIMATE CHANGE

What's happening to our planet?

INSIDE

Extreme Weather

Accelerating Pandemics

How to Save the Corals, Forests, and Other Creatures

Getting the Carbon Tax Right

What the Future Holds

SUMMER 2020

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Students in New York City in September 2019 protest for action on climate change.

FROM THE EDITOR

Our Planet, Our Choice

In September 2019 millions of workers and students around the world walked out of their schools and off their jobs to protest governments' inaction on climate change. For the protesters, the consequences of global warming were all too apparent. Last year Australia's Black Summer bushfires brought destruction and death, killing hundreds of millions of animals. Hotter conditions have triggered record-setting ice melt, heat waves, low crop yields and bleached reefs—and have even, some argue, set the scene for the novel coronavirus pandemic. Scientists have known for decades that climate change would spur dire outcomes. But in the past several years we have gained a better scientific understanding of when, where and how the impacts of global warming are being felt.

To catch up on the basics, this issue opens with a useful primer on what's happening to our planet—and dispels the tiresome arguments made by climate change deniers (*page 4*). Accelerating rates of Arctic ice melting promise to raise sea levels and displace millions (*pages 12* and *36*), and thawing permafrost threatens to double the warming that has already occurred (*page 20*).

The impacts on human society are unavoidable. Hotter air manipulates jet streams and weather patterns and fuels more extreme storms (*page 28*). Intensified floods, droughts and storms alter how and where people live and how diseases spread among us (*page 50*). Shifting climatic conditions force human emigrations and boost geopolitical tensions among nation-states (*page 58*).

The changes will affect nearly every species on earth. As the oceans absorb carbon dioxide from the air, the waters acidify and imperil creatures therein (*page 64*). Biologists are breeding heat-tolerant corals for transplantation to the most endangered reefs (*page 72*). The reproductive and migration patterns of Arctic plants and animals continue to shift (*page 68*), and to help threatened trees, dendrologists have developed a type of human-controlled artificial selection that pinpoints species better able to survive (*page 80*).

The specter of climate change is frightening, but we've also learned more about effective mitigation strategies. Urban design can ease the release of CO_2 and other harmful human outputs (*page 86*). Stronger policies that disincentivize fossil-fuel harvesting (*page 90*) and place a smart tax on carbon (*page 102*) can help us put a dent in U.S. emissions. To avoid the worst outcomes, we will likely still need to extract some CO_2 from the atmosphere, and innovative technologies are emerging to answer the call (*page 94*).

We can't mobilize these solutions soon enough. A recent report from the National Bureau of Economic Research stated that financial suffering as a result of climate change will be widespread—damaging infrastructure, gutting labor productivity and affecting agricultural yields for the worse (*page 116*). We're facing a complete reordering of the earth's ecosystems and the human societies that depend on them. No doubt remains about the problems that face our planet. But how, or if, we fix them is entirely up to us.

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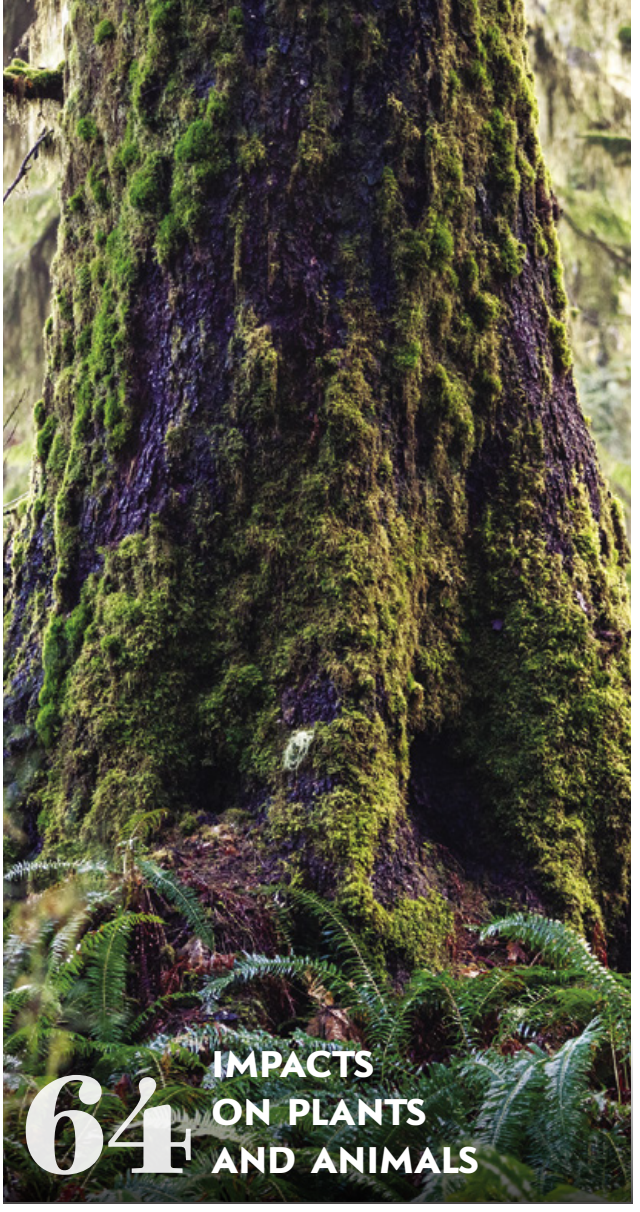

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CLIMATE CHANGE 101

SORTING FACT FROM FICTION

EVIDENCE FOR HUMAN INTERFERENCE WITH EARTH'S CLIMATE CONTINUES TO ACCUMULATE

By John Rennie

Illustration by Alison Seiffer

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PRESIDENT DONALD TRUMP HAS CONSISTENTLY OPPOSED FIGHTING CLIMATE CHANGE. His administration loosened fuel economy and emissions standards for new motor vehicles, for example—a measure that automakers had not even requested. He replaced the Clean Power Plan championed by his predecessor, President Barack Obama, with new regulations that permit more carbon emissions from coal- and gas-burning power plants. In November 2019 he even initiated the year-long process of withdrawing the U.S. from the Paris climate accords, an agreement that required nothing from its signatories except an unenforced pledge to help keep the rise in global temperatures below two degrees Celsius.

The reasoning behind those actions has been hard to pin down. Trump has repeatedly denounced global warming as a "hoax" and a Chinese plot to undermine U.S. manufacturing. But then, in a January 2019 press conference, Trump also said "nothing's a hoax" about climate change. Many of those he had named to head various agencies, including Rick Perry at the Department of Energy and Scott Pruitt at the Environmental Protection Agency, questioned or denied the role of carbon dioxide in climate change. But when reporters have directly asked whether Trump believes global warming is real, White House press secretaries have skirted the question. It's hard to tell whether his administration is skeptical about the scientific fact of the climate crisis or simply the urgency of doing anything about it.

Ambiguity has often been weaponized by those who prefer to call themselves "climate skeptics"—although they generally seem to be more dedicated to naysaying than to genuine skeptical inquiry. Not everyone who questions climate change science fits that description, of course: some people are genuinely unaware of the facts or honestly disagree about their interpretation. What distinguishes the true naysayers is their dedicated opposition to conceding that there is an actionable problem, often with long-disproved arguments about alleged weaknesses in the science of climate change.

What follows is a partial list of the contrarians' bad-faith arguments and some brief rebuttals of them.

CLAIM 1: Anthropogenic carbon dioxide can't be changing climate, because CO_2 is only a trace gas in the atmosphere and the amount produced by humans is dwarfed by the amount from volcanoes and other natural sources. Water vapor is by far the most important greenhouse gas, so changes in CO_2 are irrelevant.

Although carbon dioxide makes up only 0.04 percent of the atmosphere, that small number plays a significant role in climate

IN BRIEF

Naysayers of climate change, including members of Congress and President Donald Trump, often use weak and long-disproved arguments about alleged holes in the science behind global warming. **Human activity** is by far the largest source of carbon dioxide pumping into the atmosphere. The almost universal consensus among climate scientists is that this contribution is heating the planet and will have undeniable, adverse impacts on all ecosystems on Earth. **No other explanation**—not solar variations or a giant global conspiracy orchestrated by scientists—can account entirely for the fact that the planet is warming and CO_2 from human activity is the cause. Multiple lines of evidence, from ice cores to tree rings, support this conclusion.

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FORESTS REMOVE ATMOSPHERIC CO_2 and offset the nonhuman releases of CO_2. Human activity, combined with forest clearing (*shown here*), negates this process, however.

dynamics. Even at that low concentration, CO_2 absorbs infrared radiation and acts as a greenhouse gas, as physicist John Tyndall demonstrated in 1859. Chemist Svante Arrhenius went further in 1896 by estimating the impact of CO_2 on the climate; after painstaking hand calculations, he concluded that doubling its concentration might cause almost six degrees Celsius of warming—an answer not much out of line with recent, far more rigorous computations.

Contrary to the contrarians, human activity is by far the largest contributor to the observed increase in atmospheric CO_2. According to the Global Carbon Project, anthropogenic CO_2 amounts to about 35 billion tons annually—more than 130 times as much as volcanoes produce. True, 95 percent of the releases of CO_2 to the atmosphere are natural, but natural processes such as plant growth and absorption into the oceans pull the gas back out of the atmosphere and almost precisely offset them, leaving the human additions as a net surplus. Moreover, several sets of experimental measurements, including analyses of the shifting ratio of carbon isotopes in the air, further confirm that fossil-fuel burning and deforestation are the primary reasons that CO_2 levels have risen 45 percent since 1832, from 284 parts per million (ppm) to 412 ppm—a remarkable jump to the highest levels seen in millions of years.

Contrarians frequently object that water vapor, not CO_2, is the most abundant and powerful greenhouse gas; they insist that climate scientists routinely leave it out of their models. The latter is simply untrue: from Arrhenius on, climatologists have incorporated water vapor into their models. In fact, water vapor is why rising CO_2 has such a big effect on climate. CO_2 absorbs some wavelengths of infrared that water does not, so it independently adds heat to the atmosphere. As the temperature rises, more water vapor enters the atmosphere and multiplies CO_2's greenhouse effect; the Intergovernmental Panel on Climate Change (IPCC)

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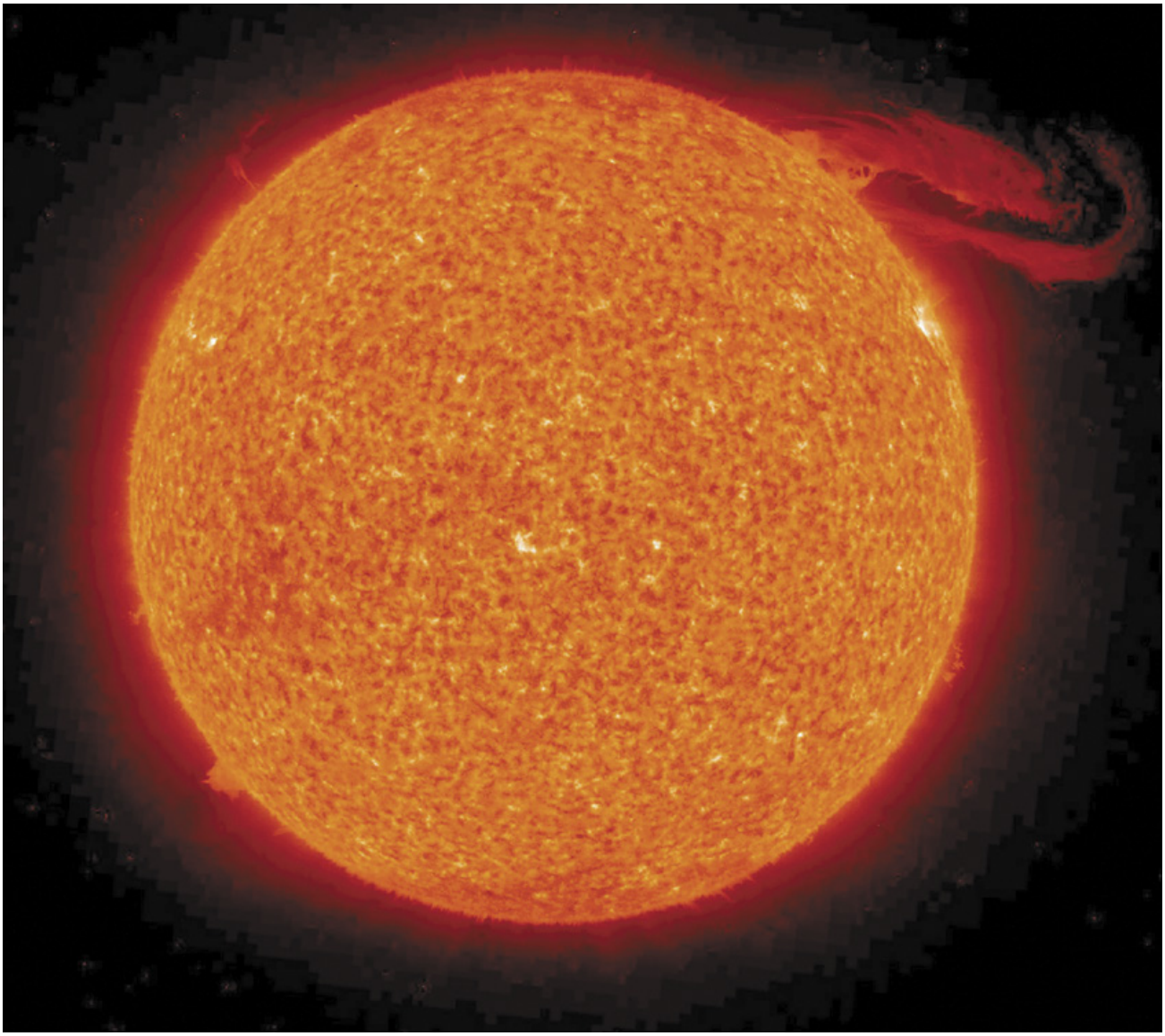

NASA

notes that water vapor may "approximately double the increase in the greenhouse effect due to the added CO_2 alone."

Nevertheless, within this dynamic, the CO_2 remains the main driver (what climatologists call a "forcing") of the greenhouse effect. As NASA climatologist Gavin Schmidt has explained, water vapor enters and leaves the atmosphere much more quickly than CO_2 and tends to preserve a fairly constant level of relative humidity, which caps off its greenhouse effect. Climatologists therefore categorize water vapor as a feedback rather than a forcing factor. (Contrarians who don't see water vapor in climate models are looking for it in the wrong place.)

Because of CO_2's inescapable greenhouse effect, contrarians holding out for a natural explanation for current global warming need to explain why, in their scenarios, CO_2 is not compounding the problem.

CLAIM 2: The alleged "hockey stick" graph of temperatures over the past 1,600 years has been disproved. It doesn't even acknowledge the existence of a "medieval warm period"

CLIMATE CONTRARIANS argue that variation in solar energy reaching the planet is behind global warming. But human influence has a measurably stronger effect on climate.

around A.D. 1000 that was hotter than today is. Therefore, global warming is a myth.

It is hard to know which is greater: contrarians' overstatement of the flaws in the historical temperature reconstruction from 1998 by Michael E. Mann and his colleagues or the ultimate insignificance of their argument to the case for climate change.

First, there is not simply one hockey-stick reconstruction of historical temperatures using one set of proxy data. Similar evidence for sharply increasing temperatures over the past couple of centuries has turned up independently while looking at ice cores, tree rings and other proxies for direct measurements, from many locations. Notwithstanding their differences, they corroborate that the planet has been getting sharply warmer.

A 2006 National Research Council review of the evidence con-

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cluded "with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries"—which is the section of the graph most relevant to current climate trends. The report placed less faith in the reconstructions back to A.D. 900, although it still viewed them as "plausible." Medieval warm periods in Europe and Asia with temperatures comparable to those seen in the 20th century were therefore similarly plausible but might have been local phenomena: the report noted "the magnitude and geographic extent of the warmth are uncertain." And a research paper by Mann and his colleagues seems to confirm that the Medieval Warm Period and the "Little Ice Age" between 1400 and 1700 were both caused by shifts in solar radiance and other natural factors that do not seem to be happening today.

After the NRC review was released, another analysis by four statisticians, called the Wegman report, which was not formally peer-reviewed, was more critical of the hockey-stick paper. But correction of the errors it pointed out did not substantially change the shape of the hockey-stick graph. In 2008 Mann and his colleagues issued an updated version of the temperature reconstruction that echoed their earlier findings.

But hypothetically, even if the hockey stick was busted … What of it? The case for anthropogenic global warming originally came from studies of climate mechanics, not from reconstructions of past temperatures seeking a cause. Warnings about current warming trends came out years before Mann's hockey-stick graph. Even if the world were incontrovertibly warmer 1,000 years ago, it would not change the fact that the recent rapid rise in CO_2 explains the current episode of warming more credibly than any natural factor does—and that no natural factor seems poised to offset further warming in the years ahead.

THE PAST 15 YEARS HAVE INCLUDED ALL 10 OF THE HOTTEST YEARS ON RECORD.

CLAIM 3: Global warming stopped in 1998; Earth has been cooling since then.

This contrarian argument might be the most obsolete and unintentionally hilarious. Here's how it goes: 1998 was the world's warmest year, according to the U.K. Met Office Hadley Center's records; the following decade was cooler; therefore, the previous century's global warming trend is over, right?

Anyone with even a glancing familiarity with statistics should be able to spot the weaknesses of that argument. Given the extended duration of the warming trend, the expected (and observed) variations in the rate of increase and the range of uncertainties in the temperature measurements and forecasts, a decade's worth of mild interruption is too small a deviation to prove a break in the pattern, climatologists say.

If a lull in global warming had continued for another decade, would that have vindicated the contrarians' case? Not necessarily, because climate is complex. For instance, Mojib Latif, then at the Leibniz Institute of Marine Sciences in Germany, and his colleagues published a paper in 2008 that suggested ocean-circulation patterns might cause a period of cooling in parts of the Northern Hemisphere, even though the long-term pattern of warming remained in effect. Fundamentally, contrarians who have resisted the abundant evidence that supports warming should not be too quick to leap on evidence that only hints at the opposite.

In any case, the claim that a "warming pause" disproved ongoing climate change became completely academic when 1998 stopped being the warmest year on record. That title now belongs to 2016, with 2019 right behind it. In fact, the past 15 years have included all 10 of the hottest years on record.

CLAIM 4: The sun or cosmic rays are much more likely the real causes of global warming. After all, Mars is warming up, too.

Astronomical phenomena are obvious natural factors to consider when trying to understand climate, particularly the brightness of the sun and details of Earth's orbit because those seem to have been major drivers of the ice ages and other climate changes before the rise of industrial civilization. Climatologists, therefore, do take them into account in their models. But in defiance of the naysayers who want to chalk the recent warming up to natural cycles, there is insufficient evidence that enough extra solar energy is reaching our planet to account for the observed rise in global temperatures.

The IPCC has noted that between 1750 and 2005, the radiative forcing from the sun increased by 0.12 watt per square meter—less than a tenth of the net forcings from human activities (1.6 W/m^2). The largest uncertainty in that comparison comes from the estimated effects of aerosols in the atmosphere, which can variously shade Earth or warm it. Even granting the maximum uncertainties to these estimates, however, the increase in human influence on climate exceeds that of any solar variation.

Moreover, remember that the effect of CO_2 and the other greenhouse gases is to amplify the sun's warming. Contrarians looking to pin global warming on the sun can't simply point to any trend in solar radiance: they also need to quantify its effect and explain why CO_2 does not consequently become an even more powerful driver of climate change. (And is what weakens the greenhouse effect a necessary consequence of the rising solar influence or an ad hoc corollary added to give the desired result?)

Contrarians therefore gravitated toward work by Henrik Svensmark of the Technical University of Denmark, who argued that the sun's influence on cosmic rays needed to be considered. Cosmic rays entering the atmosphere help to seed the formation of aerosols and clouds that reflect sunlight. In Svensmark's theory, the high solar magnetic activity over the past 50 years shielded Earth from cosmic rays and allowed exceptional heating, but now that the sun is more magnetically quiet again, global warming would reverse. Svensmark claimed that, in his model, temperature changes correlate better with cosmic-ray levels and solar magnetic activity than with other greenhouse factors.

Svensmark's theory failed to persuade most climatologists, however, because of weaknesses in its evidence. In particular, there do not seem to be clear long-term trends in the cosmic-ray influxes or in the clouds that they are supposed to form, and his model does not explain (as greenhouse explanations do) some of the observed patterns in how the world is getting warmer (such as that more of the warming occurs at night). For now, at least,

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cosmic rays remain a less plausible culprit in climate change.

And the apparent warming seen on Mars? Because it is based on a very small base of measurements, it may not represent a true trend. Too little is yet known about what governs the Martian climate to be sure, but a period when there was a darker surface might have increased the amount of absorbed sunlight and raised temperatures.

CLAIM 5: Climatologists conspire to hide the truth about global warming by locking away their data. Their so-called consensus on global warming is scientifically irrelevant because science isn't settled by popularity.

It is virtually impossible to disprove accusations of giant global conspiracies to those already convinced of them (can anyone prove that the Freemasons and the Roswell aliens aren't involved, too?). Let it therefore be noted that the magnitude of this hypothetical conspiracy would need to encompass many thousands of uncontroversial publications and respected scientists from around the world, stretching back through Arrhenius and Tyndall for almost 150 years. A conspiracy would have to be so powerful that it has co-opted the official positions of dozens of scientific organizations, including the U.S. National Academy of Sciences, the U.K.'s Royal Society, the American Association for the Advancement of Science, the American Geophysical Union, the American Institute of Physics and the American Meteorological Society.

ELEVATED CO_2 MAKES OCEANS ACIDIC, which could have irreversible harmful effects on coral reefs, such as coral bleaching (*shown here*).

If there were a massive conspiracy to defraud the world on climate (and to what end?), surely the thousands of e-mails and other files stolen from the University of East Anglia's Climatic Research Unit in England and distributed by hackers in 2009 would bear proof of it. None did. Most of the few statements from those e-mails that critics claimed as evidence of malfeasance had more innocent explanations that make sense in the context of scientists conversing privately and informally. If any of the scientists involved manipulated data dishonestly or thwarted Freedom of Information requests, it would have been deplorable; however, there is no evidence that happened. What is missing is any clear indication of a widespread attempt to falsify and coordinate findings on a scale that could hold together a global cabal or significantly distort the record on climate change.

GETTY IMAGES

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Climatologists are often frustrated by accusations that they are hiding data or the details of their models because, as NASA's Schmidt points out, much of the relevant information is in public databases or otherwise accessible—a fact that contrarians conveniently ignore when insisting that scientists stonewall their requests. (And because nations differ in their rules on data confidentiality, scientists are not always at liberty to comply with some requests.) If contrarians want to deal a devastating blow to global warming theories, they should use the public data and develop their own credible models to demonstrate sound alternatives.

Yet that rarely occurs. In 2004 historian of science Naomi Oreskes published a landmark analysis of the peer-reviewed literature on global warming, "The Scientific Consensus on Climate Change." Out of 928 papers whose abstracts she surveyed, she wrote, 75 percent explicitly or implicitly supported anthropogenic global warming, 25 percent were methodological or otherwise took no position on the subject—and none argued for purely natural explanations. Notwithstanding some attempts to debunk Oreskes's findings that eventually fell apart, her conclusion stands.

RESPONSIBLE ACTION ON CLIMATE CHANGE IS WHAT THE CONTRARIANS SEEM MOST INTERESTED IN DENYING.

Oreskes's work does not mean that all climate scientists agree about climate change—obviously, some do not (although they are very much a minority). Rather the meaningful consensus is not among the scientists but within the science: the overwhelming predominance of evidence for greenhouse-driven global warming that cannot easily be overturned even by a few contrary studies. (Oreskes currently is a columnist for *Scientific American*.)

CLAIM 6: Climatologists have a vested interest in raising the alarm because it brings them money and prestige.

If climate scientists are angling for more money by hyping fears of climate change, they are not doing so very effectively. According to the U.S. Government Accountability Office, between 1993 and 2014 federal spending on climate change research, technology, international assistance and adaptation rose from $2.4 billion to $11.6 billion. (An additional $26.1 billion was also allocated to climate change programs and activities by the economic stimulus package of the American Recovery and Reinvestment Act in 2009. Total federal nondefense spending on research in 2014 exceeded $65 billion.) Yet the scientific research share of that money fell sharply throughout that period: most of the budgeted money went to energy-conservation projects and other technology programs. Climatologists' funding therefore stayed almost flat, whereas others, including those in industry, benefited handsomely. Surely the Freemasons could do better than that.

CLAIM 7: Technological fixes, such as inventing energy sources that don't produce CO_2 or geoengineering the climate, would be more affordable, prudent ways to address climate change than reducing our carbon footprint.

Critics of standard policy responses to climate change have often seemed to imply that environmentalists are obsessed with regulatory reductions in CO_2 emissions and uninterested in technological solutions. That interpretation is at best bizarre: such innovations in energy efficiency, conservation and production are exactly what caps or levies on CO_2 are meant to encourage.

The relevant question is whether it is prudent for civilization to defer curbing or reducing its CO_2 output before such technologies are ready and can be deployed at the needed scale. The most common conclusion is no. Remember that as long as CO_2 levels are elevated, additional heat will be pumped into the atmosphere and oceans, extending and worsening the climate consequences. As climatologist James Hansen of the Earth Institute at Columbia University has pointed out, even if current CO_2 levels could be stabilized overnight, surface temperatures would continue to rise by 0.5 degree C over the next few decades because of absorbed heat being released from the ocean. The longer we wait for technology alone to reduce CO_2, the faster we will need for those solutions to pull CO_2 out of the air to minimize the warming problems. Minimizing the scope of the challenge by restricting the accumulation of CO_2 only makes sense.

Moreover, climate change is not the only environmental crisis posed by elevated CO_2: it also makes the oceans acidic, which could have irreversibly harmful effects on coral reefs and other marine life. Only the immediate mitigation of CO_2 release can contain those losses.

Much has already been written on why schemes for geoengineering—altering Earth's climate systems by design—seem ill advised except as a desperate last-chance strategy for dealing with climate change. The more ambitious proposals involve largely untested technologies, so it is unclear how well they would achieve their desired purpose; even if they did curb warming, they might cause other significant environmental problems in the process. Methods that did not remove CO_2 from the air would have to be maintained in perpetuity to prevent drastic rebound warming. And the governance of the geoengineering system could become a political minefield, with nations disagreeing about what the optimal climate settings should be. And of course, as with any of the other technological solutions, reducing the emission and accumulation of CO_2 in the atmosphere first would only make any geoengineering solution easier.

All in all, counting on future technological developments to solve climate change rather than engaging with the problem straightforwardly by all available means, including regulatory ones, seems like the height of irresponsibility. But then again, responsible action on climate change is what the contrarians seem most interested in denying.

John Rennie is a former editor in chief of *Scientific American*.

MORE TO EXPLORE

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THE ARCTIC CLIMATE IS SHATTERING

MELTD

ICEBERGS launched from Greenland's fast-moving Jakobshavn glacier float past the town of Ilulissat under the midnight sun.

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RECORD AFTER RECORD, ALTERING WEATHER WORLDWIDE

By Jennifer A. Francis

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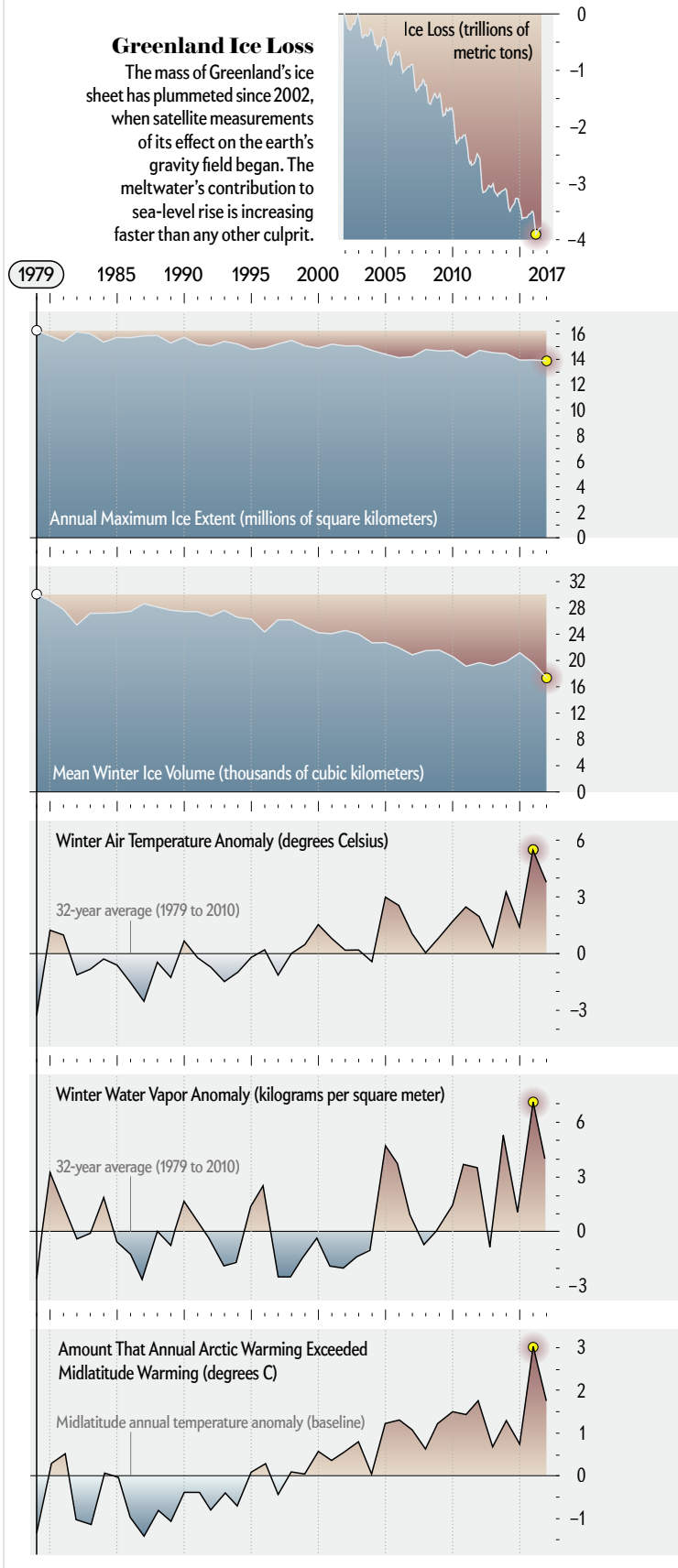
TWENTY-FIVE SCIENTISTS, including me, had an epiphany about the Arctic in 2003. The National Science Foundation had invited us to a retreat in Big Sky, Mont. Before this gathering, each of us had been focusing our Arctic research on our own narrow topics. As we shared our perspectives, we came to a frightening realization: the changes we had been finding individually were connected. They fit together perfectly. The Arctic system as a whole was careening toward a precarious new state. And hope of stopping it already seemed unlikely.

We published a paper with a stunning, controversial conclusion: At the current rate of change, there was a real possibility that within a century, the world could witness a summer Arctic Ocean that would be ice-free, a state not seen for thousands of years. Today I am startled again because it now appears that the ocean will likely be free of summer ice by 2040—a full 60 years earlier than we had predicted little more than a decade ago.

The Arctic is changing exactly the way scientists thought it would but faster than even the most aggressive predictions. The recent behavior is off the charts. Since just 2015, more than a dozen climate records that had each stood for many decades have crumbled, including those for disappearing summer sea ice, decreasing winter sea ice, warming air and thawing ground.

These trends signal trouble for people around the world. The last time the Arctic was only slightly warmer than today—about 125,000 years ago—oceans were 13 to 20 feet higher. Goodbye Miami, New Orleans, the naval base in Norfolk, Va., most of New York City and Silicon Valley, as well as Venice, London and Shanghai. New research suggests that rapid Arctic warming also tends to reroute the jet stream in ways that could allow punishing weather patterns to linger across North America, central Europe and Asia longer than usual, subjecting millions of people to unyielding heat waves, droughts or relentless



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IN BRIEF

The Arctic climate is changing rapidly, breaking at least a dozen major records since 2015.
Sea ice is disappearing, air temperatures are soaring, permafrost is thawing and glaciers are melting.
The swift warming is altering the jet stream and polar vortex, prolonging heat waves, droughts, deep freezes and heavy rains worldwide.

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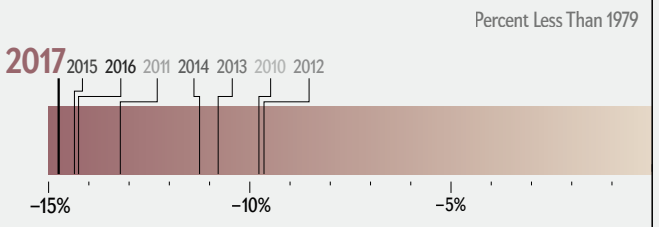
Record-Breaking Arctic

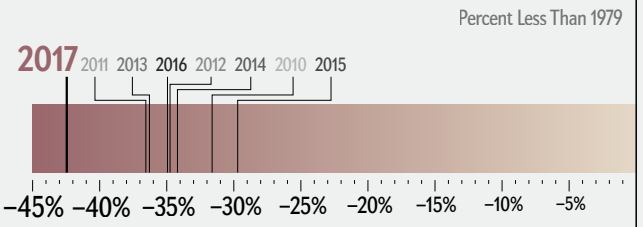
The Arctic region is changing dramatically, and the rapid transformation will affect billions of people around the world. Since 2015 alone numerous climate records up north have been broken, in some cases by stunning margins. Six notable examples are shown here. Red numbers in the bar charts indicate all-time records; values for recent years reflect a trend toward those excesses. Individually, the effects alter the environment and daily life for people throughout the region. Together the effects are reshaping weather across the Northern Hemisphere, culminating in Arctic amplification (*final graph*), which raises the chance for extreme conditions year-round.

Value in 1979



Winter Sea Ice Extent

As winter deepens, ice spreads over the Arctic Ocean. But the maximum reach has declined steadily, especially across the Barents and Bering seas. Less ice cover allows the open ocean to send more heat and moisture into the air, significantly disrupting Arctic weather.

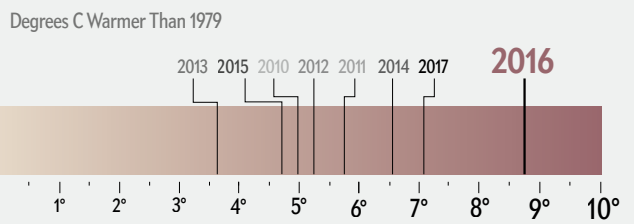


Winter Sea Ice Volume

By 2017 the amount of winter ice floating on the Arctic Ocean had dropped an astounding 42.5 percent since 1979. Winds can more easily push thin ice, trapping ships and coastal communities. Thinner ice also melts faster in warm months; summer ice volume has dropped 80 percent in the same time span.

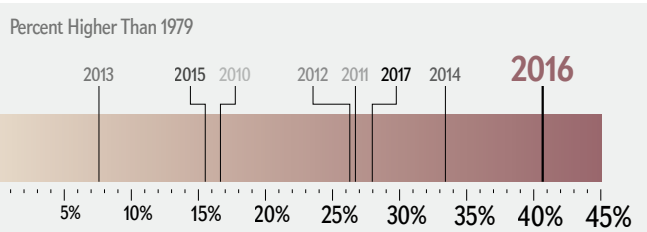
Winter Air Temperature

On certain days Arctic temperatures can soar 20 degrees Celsius above normal, and they are now elevated throughout most winters. In 2016 the mean winter temperature was almost nine degrees higher than in 1979. This trend can weaken the jet stream, bringing deep cold snaps and snows to the U.S., Europe and Asia.



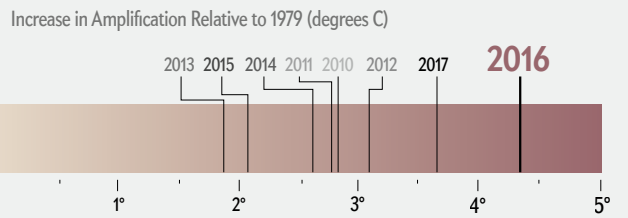
Winter Water Vapor

With less ice cover, more open ocean sends added moisture into the air. Even a small rise has big, underappreciated consequences: water vapor is a greenhouse gas that traps heat. It also condenses into clouds, releasing its latent heat. The clouds can enhance warming, too.



Arctic Amplification

The Arctic is warming faster than the rest of the world. This "amplification" means the average temperature in the Arctic is getting closer to the average temperature in the midlatitudes. The narrowing gap slows the jet stream year-round, raising the chances across the Northern Hemisphere for more persistent, extreme weather patterns—among them heat waves, floods, cold spells and maybe even longer-lasting hurricanes.



SOURCES: JPL GRACE MASCON OCEAN, ICE, AND HYDROLOGY EQUIVALENT WATER HEIGHT RL05M.1 CRI FILTERED VERSION 2. D. N. WIESE, D.-N. YUAN, C. BOENING, F. W. LANDERER AND M. M. WATKINS. PO.DAAC, JPL, APRIL 29, 2016. DATA ACCESSED FEBRUARY 14, 2018 (*Greenland ice*); JAPAN'S NATIONAL INSTITUTE OF POLAR RESEARCH AND JAXA. VIA ARCTIC DATA ARCHIVE SYSTEM (*ice extent*); PIOMAS, POLAR SCIENCE CENTER (*ice volume*); NCEP/NCAR REANALYSIS 1, PHYSICAL SCIENCES DIVISION, ESRL, NOAA (*air temperature, water vapor anomaly and amplification data*)

Graphic by Pitch Interactive

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storms. Plankton are increasing throughout the southern Arctic Ocean, which may disrupt food chains that support commercial fisheries. And the massive ice melt is adding to an enormous blob of freshwater south of Greenland that may be slowing the Gulf Stream, which could significantly change weather patterns for continents on both sides of the Atlantic Ocean.

What's driving this breakneck change?

LOSS OF "PERMANENT" ICE

SCIENTISTS EXPEND A LOT OF ENERGY watching the Arctic because it is so sensitive to climatic change. It is a "canary in the coal mine" for the earth's entire climate system. The long list of records that have been smashed during the past several years leaves no doubt that decades of unnerving climate simulations are on target. But the data say something even greater: our projections of changes on the way may be far too conservative.

In only 40 years the extent of ice across the Arctic Ocean in summer has shrunk by half. Yes, half. The volume of sea ice, year-round, is way down, too—about a quarter of what it was in the early 1980s. Until recently, scientists had thought it would take until at least the middle of this century to reach these extremes.

Summer sea ice is vanishing quickly because of feedbacks—vicious cycles that can amplify a small change. For example, when a bit of extra heat melts bright-white ice, more of the dark ocean surface is exposed, which reflects less of the sun's energy back to space. That absorbed heat then warms the area further, which melts even more ice, leading to yet more warming. In winter when the sun is not shining, other feedbacks take over. For example, sea ice floating on the Arctic Ocean acts like an insulating sheet, preventing heat and moisture under it from escaping into the atmosphere. When that ice recedes, more heat and moisture can warm the air, further retarding ice formation. Computer simulations generally show ice disappearing too slowly, contributing to the conservative estimates of future warming.

Disappearing sea ice is not the only transformation keeping researchers like me awake at night. The other two types of what used to be called permanent ice in the Arctic are also declining steeply.

Permafrost—soil that usually remains frozen year-round—has been thawing. Buildings constructed atop permafrost are collapsing, trees are toppling and roads are buckling. In addition to disrupting daily life for local residents, thawing soils also can release large quantities of heat-trapping gases into the atmosphere. When the organic matter that has been locked in permafrost for thousands of years thaws, bacteria break it down into carbon dioxide (if oxygen is present) or methane (if it is not). Arctic permafrost contains about twice as much carbon as the atmosphere holds now, so widespread thaw could greatly exacerbate global warming—which would lead to even faster thaw. Today's computer models do not adequately capture the impacts of thawing permafrost, again contributing to substantial underestimates of future global warming.

The third type of previously permanent Arctic ice is the frozen water on land, including glaciers and Greenland's enormous ice cap, which is more than a mile thick on average. Losing this ice has dire consequences worldwide because, unlike melting sea ice, the runoff into the ocean raises sea level directly. During the summer of 2016 the total mass of Greenland's ice sheet (estimated using satellite measurements of how it affects the earth's gravity) reached the smallest value since satellite observations began in 2002. The levels are also lower than any amount going back to the late 1950s, when the mass was estimated in other ways. A recent investigation suggests that the accelerating ice melt on Greenland's surface is hastened by warming effects linked to dwindling sea ice.

HOTTER, WETTER AIR

REDUCED SEA ICE and rapid Arctic warming have other far-reaching effects. The combination may alter upper-level winds so that they carry additional heat and moisture from southerly latitudes toward the North Pole. In 2012 the then-record Greenland surface melt resulted from an unusually strong and persistent ridge of high pressure in the atmosphere—a so-called blocking high. It brought not only heat and moisture from the south but also soot from wildfires around the Northern Hemisphere. That soot darkens ice and snow surfaces (lowering its albedo, or reflectivity), which then absorb more of the sun's energy, accelerating melt—another one of those vicious cycles.

Strong Arctic warming can lead to prolonged heat waves, stalled hurricanes, relentless rains and more intense fire seasons.

Blocking patterns—large eddies in the jet stream—near Greenland appear to be occurring more often in recent decades, especially in summer months, which probably accounts for at least part of the upward trend in melting. Ice-mass loss during the summer of 2016 was the third highest on record, trailing 2010 and 2012. New work by my colleagues and me suggests that the greater number of blocking highs most likely is tied to global warming. Computer simulations struggle to form and break down blocks realistically, however, so it is hard to say how these patterns may act in the future.

Other Arctic behavior is equally outlandish. During the winters from 2016 to 2018, record-breaking heat waves near the North Pole were surpassed by more record-breaking heat waves. Waning and thinning sea ice is part of the cause, providing less of a barrier for the ocean's heat to enter the air. The jet stream's wild north-south swings also brought record pulses of warmth and moisture to far northern latitudes. Scientists and Arctic residents often fail to appreciate the strong effects that the extra moisture can create. For starters, water vapor is a greenhouse gas, so in a dry Arctic winter atmosphere, a little more moisture can trap substantially more heat. Moreover, when that moisture condenses into clouds, it releases latent heat, further warming the air. Finally, more clouds trap more warmth below them, one more factor contributing to the Arctic meltdown.

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MELTWATER atop a disintegrating ice cap in Svalbard, Norway, pours into the sea.

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STUCK IN EXTREMES

ALTHOUGH WE HAVE MORE TO LEARN, it has become clear that rapid Arctic change is underway, the most dramatic in human history. Given this stark reality, atmospheric scientists are trying to pin down the effects that the changing Arctic may have on people and ecosystems around the world so society can decide how to react and prepare for the future.

An obvious example of global effects is coastal flooding. According to a 2017 report by the Union of Concerned Scientists, about 170 U.S. coastal communities will experience chronic inundation within 20 years. By the end of this century, if nations keep emitting carbon dioxide as they have been, most large coastal cities around the world will face regular, disruptive flooding. This eerily prescient report was published just weeks before Hurricanes Harvey, Irma and Maria capped the U.S.'s most destructive and costly hurricane season ever.

There is also mounting evidence that strong warm-ups in the Arctic's lower atmosphere can affect winds in the jet stream and even higher, in the stratosphere, home to the polar vortex wind pattern that circles the Arctic. Northward peaks and southward valleys in the bending jet stream generate the high- and low-pressure centers we see on weather maps as a capital H or L. The bends control our weather in the Northern Hemisphere. But if extremely large bends occur more often, we can expect to see an uptick in extreme conditions where billions of people live. That is because large bends in the jet stream tend to progress more slowly from west to east, causing the weather systems they create to hang around longer. Think prolonged heat waves, relentless rains and stalled tropical storms like Hurricane Harvey, which swamped Houston in August 2017—as well as more intense fire seasons like the ones California has experienced in recent years.

Large waves in the jet stream, along with strong Arctic warming, can disrupt the polar vortex, prolonging deadly deep freezes or parades of snowstorms, including the long stretch of severe cold that gripped the northern U.S. in early January 2018. A polar vortex collapse can also perpetuate wild jet-stream swings that deliver crazy heat waves to Alaska and the far north, creating yet another vicious cycle that accelerates Arctic warming. Some studies suggest that Arctic warming is closely connected with these wavy patterns; others say proof of the connection is still tenuous. Research on this hot topic is advancing quickly.

A rapidly warming Arctic most likely will significantly alter habitats on land and at sea. Already, as sea ice recedes, plankton blooms have appeared in new areas during new seasons, enticing species of fish from lower latitudes to move into Arctic waters while native fish disappear. Earlier spring snowmelt across high latitudes has led to earlier greening of the tundra and earlier hatching of insects; migrating birds, which take their cues from the length of daylight hours, may arrive at Arctic food sites too late for the feast. Peoples of the Arctic are feeling the impacts, too; melting ice is keeping them from traditional hunting grounds and even forcing them to uproot towns threatened by coastal erosion from high storm waves in areas that used to be protected by ice along the shore. At the same time, big countries and big companies are swooping in to search for newly accessible natural resources, as tensions rise over who can claim which parts of the vast, rich seabed as theirs.

The revelation my colleagues and I had at the Big Sky retreat replays in my head every time another long-lived weather pattern wreaks havoc or another Arctic record is broken. Now my neighbors are catching on. Polls suggest that most Americans think that the loss of Arctic ice and the jet stream—which has fast become a household term—are conspiring to create weird weather. The old Arctic may have been ruthless, but it was stable. The new Arctic is less predictable and may be changing in ways that are irreversible, with ripple effects on life around the globe.

Are these impacts still avoidable? Yes and no. Because the climate's response lags behind the increases in greenhouse gas concentrations and because carbon dioxide has a very long lifetime in the atmosphere, future change is already baked into the system. But the magnitude and pace can be reduced if society moves quickly to slow emissions and if methods can be developed to extract carbon from the atmosphere in large quantities. Progress on both these fronts is rapid, though likely too little, too late, to preserve the earth and the Arctic as we have known them. Prepare for the unexpected. SA

Jennifer A. Francis is a senior scientist at the Woods Hole Research Center in Falmouth, Mass. She was a research professor at Rutgers University from 1994 to 2018. Francis serves on *Scientific American*'s board of advisers.

MORE TO EXPLORE

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Amplified Arctic Warming and Mid-latitude Weather: New Perspectives on Emerging Connections. Jennifer A. Francis, Stephen J. Vavrus and Judah Cohen in *WIREs Climate Change*, Vol. 8, No. 5, Article. No. e474; September/October 2017.

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How Hot, Exactly, Is It Going to Get?

The latest climate models about global warming are giving disturbing answers

By Kate Marvel

IMAGINE SPENDING YOUR WHOLE CAREER working on a question to which you don't want to know the answer. We know that greenhouse gas emissions can and do warm the planet, but we don't know one very basic thing: How hot, exactly, is it going to get? The main reason for this, of course, is that human behavior is so hard to predict. How will the people of the late 21st century get their energy? Will they need as much as we do, or will they have fundamentally different lives?

Perhaps that decision will have been made for them by war or societal collapse. None of this is knowable. But even if we could remove all the uncertainty associated with politics, economics, technology and demography, we still wouldn't be sure. There are many things we don't understand about our rapidly warming planet.

To some extent, we know why we don't know. I have been sternly informed by communications experts that "global warming" is a better term for what's happening than "climate change." I have also been told the opposite. Yet the two are inseparable: they feed back on each other. Rising temperatures change the planet, and these changes can speed up or, if we are very lucky, slow down the warming we've caused.

We are not very lucky. Most of these changes will make things worse. The polar ice that we are currently melting is a good example. Right now it reflects sunlight back to space, cooling the planet like a sunscreen on a car windshield. When it goes, it will leave behind dark land or ocean to absorb rather than reflect the sun. A little bit of warming can become much more.

To study the effects of these changes, we use something artificial but useful: the concept of climate "sensitivity." In our climate models, we abruptly double atmospheric carbon dioxide from its preindustrial value of 280 parts per million, let the model Earth evolve for a few hundred years and then measure the increase in its temperature. In the first generation of climate models, this varied from about 1.5 degrees Celsius to about 4.5. The best guess was about three degrees C. The next time we did this, having improved the models substantially, the best guess was three degrees, and the range was between 1.5 and 4.5 degrees. After decades of new science and advances in computing power later, nothing about these estimates or their uncertainty has substantially changed.

We don't know everything, but we know more than nothing. All climate models simulate a changing planet in response to a changing temperature. And increasingly, we know why they disagree on that final warming. In the climate models that warm, more low, thick clouds appear to be changing in ways that reduce their sun-blocking power. In the models that warm less, these changes are smaller.

So scientists have devoted their time to measuring clouds, understanding them and figuring out how to represent them in climate models. This work has paid off: the range of uncertainty is now changing. Unfortunately, it has increased. Climate models that use more modern techniques to simulate clouds are now projecting more warming: five or six degrees C in response to a doubling of carbon dioxide. To put those numbers in context, 4.5 degrees is the difference between now and the last ice age.

I find these high numbers hard to believe, but as a scientist it's my job to find things hard to believe. My skepticism is rooted in clues from the planet's past. At the height of the last ice age, temperatures were cooler and carbon dioxide levels lower. It's hard to reconcile these measurements with extremely high climate sensitivities. But it's almost impossible to reconcile them with extremely low ones.

Clues from the more recent past might seem to paint a more reassuring picture. We have, after all, emitted carbon dioxide, and the planet has warmed in response. Earth is about one degree C warmer than it was before the Industrial Revolution. This is dangerous but not yet catastrophic, and some have suggested that it might be indicative of a planet relatively insensitive to carbon dioxide. But the past is not the future, and we have good reason to believe that there are no analogues for the future into which we are hurtling. Right now heat is being mixed into the deep ocean, which is cold and vast but not infinite. It will warm up in time, over hundreds or thousands of years, and the changes it

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will trigger may be different than any we have ever observed. Clouds may dissipate, ice will melt and the warming will get worse.

These uncertainties matter in the real world. If the climate is very sensitive to carbon dioxide—if the changes provoked by warming themselves create much more warming—then our time frame for action is reduced. If the climate is relatively insensitive, then perhaps we'll have a little more breathing room. But we have ruled out a climate sensitivity of zero. Warming is real, it's happening and it's likely to get worse. Uncertainty is no excuse for inaction. Even in the improbable event that climate sensitivity is very low, "business as usual" still warms the planet and leads to unpleasant consequences. In the event that climate sensitivity is high, "business as usual" means disaster.

Climate models, like all models, are imperfect representations of the real world. They tell us something useful about the planet we are changing but not how much, exactly, we'll change it. The only way to be sure is to actually double atmospheric carbon dioxide and wait until the planet approaches a new equilibrium, measuring the changes along the way. This is an uncontrolled experiment I hope will never come to pass. But I'm afraid we're well on our way to finding out what will happen if it does. SA

Kate Marvel is a climate scientist at Columbia University and NASA's Goddard Institute for Space Studies. She received a Ph.D. in theoretical physics from the University of Cambridge and has worked at Stanford University, the Carnegie Institution and Lawrence Livermore National Laboratory. Her writing has appeared in *Scientific American,* the On Being podcast and *Nautilus* magazine. Marvel has given talks in places as diverse as comedy clubs, prisons and the TED main stage.

MORE TO EXPLORE

Causes of Higher Climate Sensitivity in CMIP6 Models. Mark D. Zelinka et al. in *Geophysical Research Letters,* Vol. 47, No. 1, Article e2019GL085782; January 16, 2020.

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SCIENTISTS drill out a meter-long core of permafrost soil at the Eight Mile Lake research site near Healy, Alaska, in September 2016. The dark color and texture (*opposite page*) indicate the soil is packed with organic matter that can decompose and give off greenhouse gases.

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THE PERMAFROST PREDICTION

Thawing Arctic tundra will likely speed up climate change for a century or more. The question is: How drastically?

By Ted Schuur

IN BRIEF

Permafrost—soil frozen year-round—is thawing widely across the Arctic. Microbes are breaking down plant and animal remains in the warming soil, releasing carbon dioxide and methane to the atmosphere.

The Northern Hemisphere permafrost region is vast, containing 1,460 billion to 1,600 billion metric tons of organic carbon, almost twice as much carbon as exists in Earth's atmosphere.

Data from numerous sensors suggest that 5 to 15 percent of that carbon could escape this century. At 10 percent, 146 billion to 160 billion metric tons of carbon would enter the atmosphere, accelerating global warming. Slowing overall warming is the best way to prevent permafrost from heating up.

Photographs by Brian Adams

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THE SOLID, 20-KILOGRAM BLOCK OF HARDENED snow and ice somehow slides free from my rubber-gloved grasp and drops back down into the long ditch I am excavating in deep snow, landing with a crunch. On my knees at the edge of the trench, I straighten up to catch my breath and arch my sore lower back, protected with a weight-lifting belt. On this bright, cold day in interior Alaska, five scientists and I are digging out tons of snow along the fourth of six snow fences positioned on a gradual hill on the tundra, hauling it away on sleds. Our labor is part of an experiment designed to warm the ground, simulating what future climate may do in this remote location just outside of Denali National Park.

It is early April, and my team is spending more than a week removing compressed snowdrifts that have accumulated along the fences we install every fall at the site. Each fence is about one and a half meters high and eight meters long. The extra snow insulates the ground from the frigid winter air like a blanket, keeping the surface of permafrost—soil that usually remains frozen year-round—warmer than it otherwise would be. We remove the excess snow so that spring's impact penetrates our experimental plots at the same time as the surrounding tundra region and so that no extra meltwater percolates down into the ground, altering the soil in comparison with that in the larger area.

Keeping the frozen soil warmer during winter causes it to thaw sooner and more extensively in the summer. This reaction is exactly what is projected to occur as temperatures rise across the tundra and boreal ecosystems just south of the Arctic, which is happening twice as fast as the increasing global average. Permafrost contains rock, frozen soil and ice, so it thaws, rather than melts, when it warms. Like hamburger pulled from your freezer, it softens but does not become liquid. As permafrost thaws, previously frozen microbes reactivate and decompose the remnants of plants and animals accumulated into the frozen soil over hundreds to thousands of years, giving off carbon dioxide and methane.

The permafrost region that circles the northern part of Earth holds so much organic material in soils that releasing just a fraction of it as greenhouse gases into the atmosphere would dramatically raise the rate of global warming. Our experiment in Alaska is one important part of integrated research around the world to figure out how big this effect is likely to be over the coming decades. We are now starting to know enough to make solid predictions.

VAST QUANTITIES COULD THAW

HOW CAN WE POSSIBLY put a number on how much permafrost will thaw, and how fast, and how much the carbon release will affect global warming? A quantification would have to assess a massive area of the planet. The permafrost region extends across 16.7 million square kilometers of the Northern Hemisphere, almost one quarter of the ice-free land area. And the frozen ground can be tens to hundreds of meters deep. (Much of the Southern Hemisphere's high latitudes is covered by ocean or ice sheets on land, so permafrost extent there is limited.)

Although satellites and remote-sensing equipment can accurately record changes in ice sheets such as those on Greenland, there is no comprehensive remote-sensing system for permafrost regions. For years scientists monitored ground sensors installed in certain permafrost spots, but we just did not have enough data points worldwide. We have steadily added more sensors, however. The Global Terrestrial Network for Permafrost now tracks more than 1,000 boreholes lined with instruments that monitor temperatures in the top few meters of soil as well as deeper underground.

The network has shown that permafrost has been warming steadily over the past several decades, setting new records in 2014 and 2015 at many locations. The most dramatic increases have occurred where soil temperatures have historically been very cold, from –10 to –5 degrees Celsius. We have also seen increases in temperature in permafrost that is closer to the freezing point, from –2 to zero degrees C, where a one-degree change can have a big impact. In some locations where permafrost is

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SENSORS in white chambers near the snow-capped Alaska Range measure the soil's uptake and release of carbon dioxide (*1*). Researcher Meghan Taylor of Northern Arizona University records the data (*2*).

just below the freezing point, the active layer—soil at the surface that thaws during summer and refreezes in winter—is becoming thicker. When we stitch together all these measurements worldwide, we get a good sense of soil-temperature change across the Arctic.

How much permafrost could thaw is only part of the calculation we want to make. We also need to know how much organic matter the softening soil contains. In spring at the Eight Mile Lake research site, my team routinely drills down into the ground and pulls out cores of soil 1.5 meters deep, as we have done in various years since the project began more than a decade and a half ago. Measurements by us and others across the tundra show that the top cubic meter of soil contains about 50 kilograms of organic carbon—carbon bound up in those partially decayed but frozen organisms (as opposed to inorganic carbon that is part of rock, unlikely to change regardless of temperature). That amount is about five times as much carbon as in nonpermafrost soils within the same region and about 100 times as much as is stored in shrubs and other plants that eke out a living in the Arctic.

Carbon can exist tens of meters down into the ground, too. Overall, researchers estimate that 1,460 billion to 1,600 billion metric tons of organic carbon is stored in Northern Hemisphere permafrost, almost twice as much carbon as exists in Earth's atmosphere. The top three meters of soil in the northern permafrost region alone hold 50 percent as much carbon as the top three meters of soil everywhere else on the planet, even though the region represents only 15 percent of the global soil area.

Scientists are also measuring organic carbon in places where we never have, such as permafrost that is submerged at the bottom of very shallow seafloors along parts of the Arctic coast. This permafrost is slowly degrading as seawater seeps into it, and we are not yet clear on how much organic carbon may be there. Carbon is also plentiful in thick sediments in vast Arctic river deltas, but we simply have not measured many sites. The best we can suggest at this point is that about 400 billion metric tons of additional carbon may be preserved in these disparate places.

HOW MUCH, HOW FAST?

GIVEN THE VAST STORES of organic carbon in permafrost, it seems plausible that thawing could release massive quantities of greenhouse gases. Pinning a number on that release depends on three key questions.

First, how much of the carbon might be converted into greenhouse gases? Microorganisms can easily metabolize and release some of the carbon but not all. As a result, some fraction of the carbon will simply remain in the ground because it is so inaccessible or inedible by microbes.

Second, how fast will microbial action release gases? Rapidly decomposing carbon can become airborne in less than a year after thaw, but more of the carbon will most likely be released gradually over decades after thaw, in part because it is already in a semidecomposed state that microbes only further degrade slowly.

The third key question is: Which greenhouse gases will the microbes release? The mix of carbon dioxide and methane will determine the ultimate climate warming potential. Waterlogged, low-oxygen soils (known as anaerobic environments) such as peat

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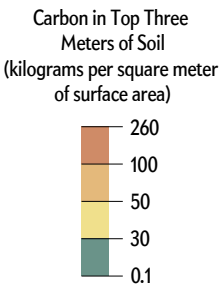
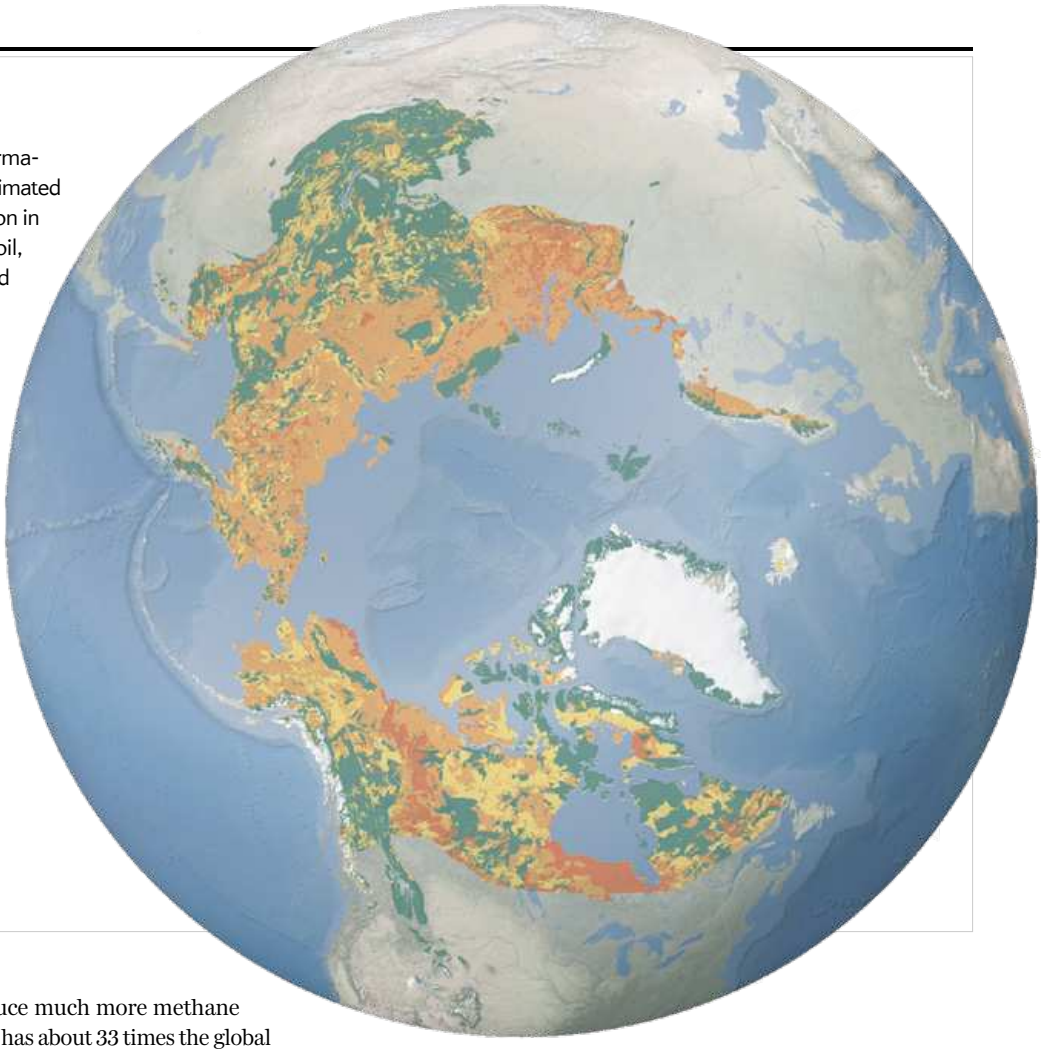
Carbon Pool

The Northern Hemisphere's permafrost zone (*colors*) contains an estimated 1,035 billion metric tons of carbon in the top three meters of frozen soil, which could escape if the ground thaws, amplifying global warming significantly. Permafrost is nearly everywhere in the northernmost regions. It is more discontinuous farther south, but many areas in both regions contain high carbon concentrations (*red* and *orange*).





bogs, for example, typically produce much more methane than carbon dioxide, and methane has about 33 times the global warming potential of carbon dioxide by weight over a century.

We track gas release at study sites such as Eight Mile Lake and the surrounding tundra with infrared gas analyzers that measure concentrations in the air across seconds, days, seasons and years. The tundra at Eight Mile Lake appears to be losing more carbon to the atmosphere than it is absorbing. Warming the ground with snow along the fences helps plants grow faster and larger, pulling and storing more carbon dioxide from the air. But it also helps microbes decompose more carbon in the soil. In the summertime, the extra plant growth completely offsets additional carbon release from the soil, but continued microbial activity throughout the long autumn and winter, when plants are dormant, shifts the annual balance to net carbon loss to the atmosphere.

When we combine our results with those from other types of experiments around the world, we conclude that thawing permafrost is spewing excess carbon into the atmosphere. Researchers bring data together through the Permafrost Carbon Network. Just like the parable of the blind men describing the elephant, field researchers across the Arctic each have important and unique information that when linked together creates knowledge about the true size and nature of this phenomenon. The Permafrost Carbon Network also synthesizes science results for reports, agency briefings and media interviews to inform decision makers and the wider public so these groups can decide how to respond to our changing Earth.

One recent synthesis project has helped answer the question about relative releases of carbon dioxide and methane. In aerobic conditions (dry soils), microbes mostly release carbon dioxide. But in anaerobic conditions in wetlands and peat soils, they release both carbon dioxide and methane. Christina Schädel, an assistant research professor at Northern Arizona University working with my group and a key player in the Permafrost Carbon Network, has been studying how this trade-off might ultimately affect climate.

In contrast to our field study, Schädel relied on experiments where frozen soil was taken into the laboratory and warmed in glass chambers so that the amount and rate of soil carbon converted into carbon dioxide or methane could be measured precisely. She used statistical techniques to bring data together from tests such as these around the world and has found that carbon dioxide is the predominant greenhouse gas by weight that is released by identical soil samples regardless of whether they were found in either aerobic or anaerobic conditions. Surprisingly, the climate impact of greenhouse gas release from aerobic decomposition is two times larger than for anaerobic decomposition, despite the additional potency of methane, which is released only from the latter.

The implication is that permafrost thaw in relatively well-drained, upland soils most likely will have a greater impact on

SOURCE: "CLIMATE CHANGE AND THE PERMAFROST CARBON FEEDBACK," BY E.A.G. SCHUUR ET AL., IN *NATURE*, VOL. 520; APRIL 9, 2015

Map by Mapping Specialists

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climate than a similar amount of thaw in lowland, waterlogged soils. Although methane is still a key part of the equation, the overall distribution of upland and lowland environments across the Arctic landscape will significantly determine permafrost thaw's impact on climate.

ACCELERATING CLIMATE CHANGE

BY SYNTHESIZING DATA from field sites and lab tests and combining that information with computer simulations of future climate scenarios, the Permafrost Carbon Network has generated an answer to the overarching question of how permafrost thaw might affect climate. In the expert judgment of its members, between 5 and 15 percent of the permafrost carbon pool is likely to be released this century, most of it as carbon dioxide.

The midrange—10 percent—of the carbon pool, as best we know it, means that 146 billion to 160 billion metric tons of additional carbon would enter the atmosphere. That amount, if released primarily in the form of carbon dioxide at a constant rate over a century, would be similar to the amount of carbon released worldwide thus far by deforestation and other land-use changes but much less than that from fossil-fuel emissions. Permafrost thaw will make climate change happen even faster than scientists project based on emissions from human activities alone. And permafrost carbon emissions are likely to continue beyond this century. Each additional ton of carbon released from the thawing Arctic into the atmosphere will impose additional costs on society.

Reducing permafrost thaw with some kind of local fixes across the Arctic is not a realistic option. The only real solution is to limit emissions from fossil fuels and from deforestation to slow global warming overall. That in turn will reduce emissions from Arctic thaw, giving communities at all latitudes more time to adapt.

Scientists generated the 5 to 15 percent number for the first time only in 2016. We still do not have a comprehensive observation system in permafrost regions to make a firmer prediction. More sensors would allow us to better detect both slow and rapid change, which could be cause for either lessened or heightened concern. And they would help us detect important surprises that might arise.

Initiatives, such as the U.S. Department of Energy's Next-Generation Ecosystem Experiments–Arctic project and NASA's Arctic-Boreal Vulnerability Experiment, are helping to fill in important gaps in modeling and in scaling up site-based measurements such as those from Eight Mile Lake to the surrounding region and, ultimately, to the global scale.

One intriguing and critical question is whether extensive plant growth could counterbalance permafrost carbon release. The latest simulations tend to show that longer growing seasons, warmer temperatures, more plant nutrients released by decomposing soils, and natural shifts to faster-growing plants and trees might offset carbon release from permafrost during this century. But that assessment contradicts measurements from Eight Mile Lake and elsewhere, which show net carbon loss across an entire year.

Better simulation of how thawing ground subsides would also be useful; it is currently missing from large-scale models that simulate the permafrost carbon and climate interactions. As ice in permafrost melts and drains away, the ground subsides, which then causes permafrost to thaw more abruptly. Could widespread subsidence boost emissions forecasts even more?

My colleagues and I saw this very effect at Eight Mile Lake when we returned there in spring 2016. The boardwalks we had built almost a decade before, along with the gas-flux monitors and other gear we had installed, had become twisted and angled from ongoing subsidence. The ground was undulating and pitted.

INSTRUMENT TOWER measures carbon dioxide and methane transfer between the air and soil year-round, indicating whether the ecosystem experiences a net gain or loss of gases annually.

The spring 2016 thaw at Eight Mile Lake also went deeper than ever—more than a meter in some spots, an amount typically seen only at the end of summer in previous years. The unusual readings paralleled similar extremes elsewhere in the Arctic: record, early-season retreat of winter ice cover on the Arctic Ocean, early snowmelt across the Northern Hemisphere and early surface melt of the ice sheet in Greenland. Carbon emissions from permafrost are happening right now. The release of gases will not be a rapid burst that could alter climate abruptly, as some feared. But it will indeed be widespread and sustained over many decades, seriously compounding the daunting challenge that society already faces to slow global warming. SA

Ted Schuur is a professor of ecosystem ecology at Northern Arizona University. He has conducted almost two decades of field research across the Arctic. He is also the lead investigator for the Permafrost Carbon Network, an international consortium of researchers that synthesizes new findings about permafrost carbon and climate.

MORE TO EXPLORE

Expert Assessment of Vulnerability of Permafrost Carbon to Climate Change. E.A.G. Schuur et al. in *Climatic Change,* Vol. 119, No. 2, pages 359–374; July 2013.
Climate Change and the Permafrost Carbon Feedback. E.A.G. Schuur et al. in *Nature,* Vol. 520, pages 171–179; April 9, 2015.
Polar Regions. M. Meredith et al. in *Special Report on the Ocean and Cryosphere in a Changing Climate.* Edited by H.-O. Pörtner et al. IPCC, 2019. Available at www.ipcc.ch/srocc

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This Was the Decade We Knew We Were Right

Everything is connected, and everything is changing

By Kate Marvel

A STATE OF EMERGENCY WAS DECLARED on November 11, 2019, and residents in the Sydney area were warned of "catastrophic" fire danger as Australia prepared for a fresh wave of deadly bushfires that had ravaged the drought-stricken east of the country.

It rains in the Amazon because the trees want it to. There is plenty of moisture in the oceans that surround the continent, but there is also a hidden reservoir on the land feeding an invisible river that flows upward to the sky. The water held in the soil is lifted up by the bodies of the trees and lost through the surfaces of their leaves to the atmosphere. The local sky plumps with moisture, primed for the arrival of the seasonal rains driven by the annual back-and-forth march of the sun's rays. As climate scientist Alex Hall puts it, the trees are co-conspiring with the sky to attract an earlier monsoon.

This is the decade we knew we were right. It began with the warmest year on record; it then broke that record at least five times. Carbon dioxide in the atmosphere reached levels unprecedented since humans were hominins. There were

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droughts and floods and brutal heat waves. Coral reefs turned white and gave up. Australia is in drought. The Amazon is on fire.

Nothing is eternal, and nothing is infinite. There were once forests in the Sahara—if not quite the Amazon, still lush and tropical, clustered around the largest freshwater lake on the planet. In geologic time, this was practically yesterday: less than 10,000 years ago. The lake is mostly gone now, vanished in the span of a few hundred years. In its place there is nothing but dust.

The changes now are different. We expected most of them, and they are occurring with a terrifying rapidity that is no more reassuring because it is easily understood. We have known that carbon dioxide traps heat for more than 100 years. We have known that we are changing the planet for decades now. There is no consolation in being right.

The climate always changes. It is dry in the Sahara because the planet wobbled slightly in its orbit, weakening the monsoon rains in the west of Africa. The plants sucked the moisture from the soil; it was not replaced. They died, and no more moisture entered the atmosphere: a vicious cycle of dying and drying that led to the dusty, depopulated desert we know today. This was climate change; it was likely not the fault of humans. But the existence of past climate change does not mean we are not responsible for it this time. There have always been gentle and natural deaths. This does not make murder impossible.

The decade began with lies and ended with evasions. Hackers, probably Russian, stole the e-mails of a few scientists and offered single sentences, taken wildly out of context, to an eager and credulous media. We heard both sides: the truth and the not-truth and were encouraged to draw our own conclusions. The temperature rose; physics was not watching the debate. We learned nothing from the experience.

The winds over the Sahara come from the East, dense, sinking forced sideways as Earth rotates away underneath it. The dust is carried across the Atlantic, enlarging the beaches of the Caribbean, scattering low-angle sunlight into brilliant purple-orange sunsets, and landing gently on the forests of the Amazon. But the air over the Sahara has arrived from the tropics, rising and shedding its moisture on a journey toward the poles. When it can go no farther, it cools and sinks. There are no deserts without the tropics.

Everything is connected. Children were murdered in their schools and were angry about it. Children saw their futures bargained away for short-term profit and were angry about it. Children saw the changing world and were angry about it. The streets swelled with angry children and heartbroken parents, a chorus of hurt that would have echoed through the halls of power had they been able to hear. Nothing was done, and the anger grew louder. This was the decade we saw that history was renewable. We promised to make more of it.

If you want to see the future of the Amazon, you must use physics and assumptions and know that you are almost certainly wrong. All models are wrong, but all climate models strive to be useful, to show a plausible future that may still be avoidable. If the future atmosphere is larded with even more carbon dioxide, the plants of the Amazon will not need to open the pores on their leaves quite so much to take in the gases they need. They will expel less water from these shrunken pores into the atmosphere. The trees will lose their ability to summon the monsoon. There will be fire and drought. Where there was once forest will be only dust.

THE AMAZON EXISTS BECAUSE THE SAHARA DOES, THE DESERT IS THERE BECAUSE THE TROPICS ARE HERE. NONE OF THIS WAS EVER GOING TO STAND ALONE.

Here is one thing worth remembering in the dark days of the northern midlatitude winter. The rain forest is so lush that it cannot fertilize itself. Every nutrient is seized by the greedy vegetation, locked up in the bodies of plants before it can leach into the soil. But the forest is fertilized, given life by the dead lake in the Sahara. There is phosphorus in the lake bed, turned into dust and swept across the Atlantic by the prevailing winds.

From the old comes the new, a fragile phoenix borne upward from the tropics on the rising updrafts of thick convective cloud. The Amazon exists because the Sahara does, the desert is there because the tropics are here. None of this was ever going to stand alone. SA

Kate Marvel is a climate scientist at Columbia University and NASA's Goddard Institute for Space Studies. She received a Ph.D. in theoretical physics from the University of Cambridge and has worked at Stanford University, the Carnegie Institution and Lawrence Livermore National Laboratory. Her writing has appeared in *Scientific American*, the On Being podcast and *Nautilus* magazine. Marvel has given talks in places as diverse as comedy clubs, prisons and the TED main stage.

MORE TO EXPLORE

Twentieth-Century Hydroclimate Changes Consistent with Human Influence. Kate Marvel, Benjamin I. Cook, Céline J. W. Bonfils, Paul J. Durack, Jason E. Smerdon and A. Park Williams et al. in *Nature*, Vol. 569, pages 59–65; May 1, 2019.

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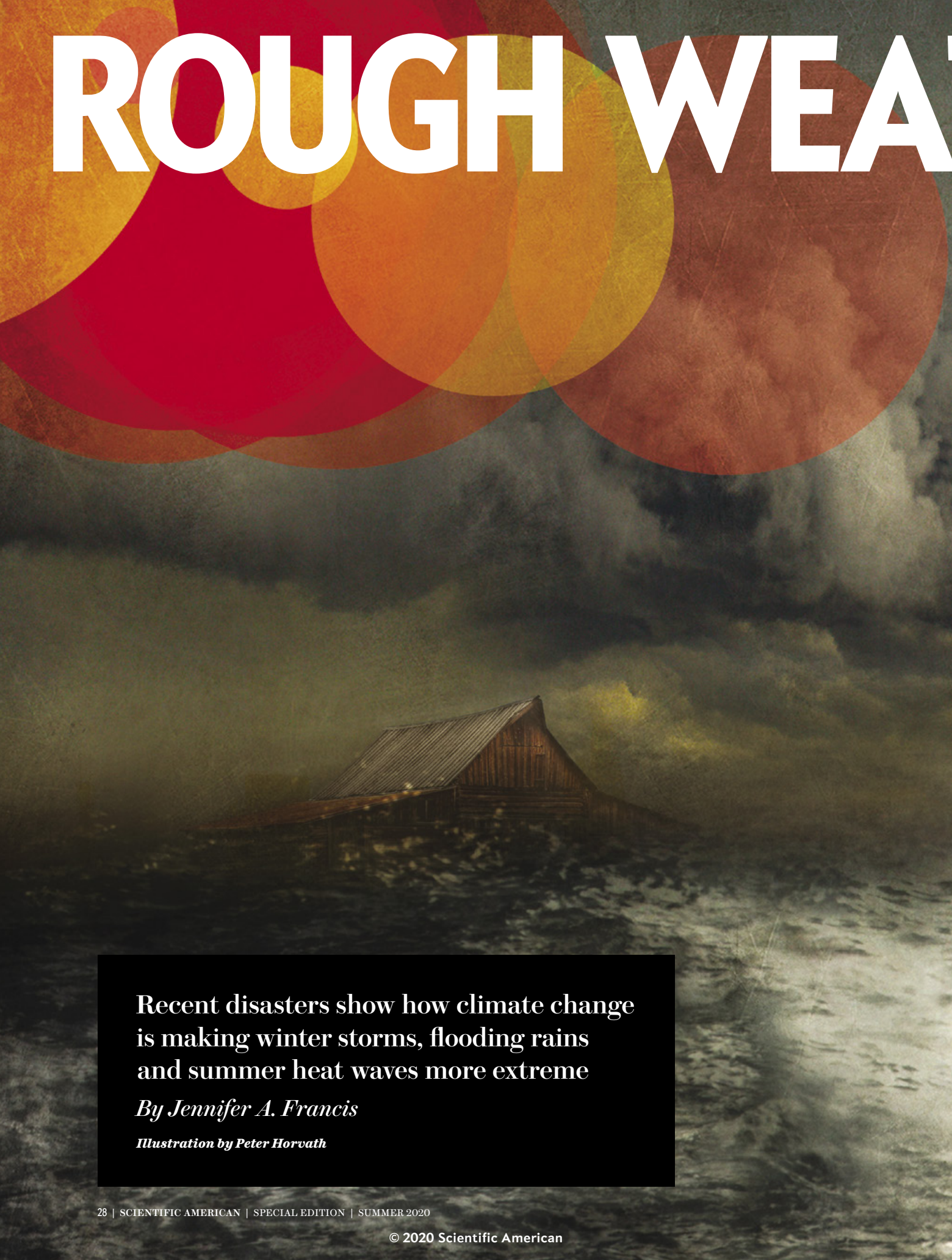
ROUGH WEA



Recent disasters show how climate change is making winter storms, flooding rains and summer heat waves more extreme

By Jennifer A. Francis

Illustration by Peter Horvath

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SHE WAS BORN IN THE USUAL way. A disorganized blob of clouds emerged over the Atlantic Ocean off Africa's bulging western coast, just north of the equator. Atmospheric pressure there was low, typical for late summer. Natural variability in the earth's climate spawns tropical disturbances every year in this area—sometimes more, sometimes fewer, and sometimes they become hurricanes. Weather forecast models unanimously predicted that the clouds would coalesce into a storm that curved harmlessly northwest into the mid-Atlantic, far from land.

On September 1, 2018, tropical storm Florence began to do just that but then turned stubbornly westward while becoming better organized, seemingly aimed at the Caribbean. Another worrisome disturbance was already lurking near Puerto Rico, which was still reeling from Hurricane Maria's devastation a year before. Three major cyclones were also spinning in the tropical Pacific, fueled by ocean temperatures that were off the charts. The mob of storms drew energy from record-warm ocean temperatures, which have risen steadily since the 1970s in lockstep with increasing atmospheric temperatures, driven by heat-trapping greenhouse gases—global effects of climate change. Storms feed off ocean heat and water vapor in the atmosphere, which is climbing as well.

Conflicting factors kept Florence weak, however. Although that seemed fortunate, it provoked anxiety among forecasters. Weaker storms are more readily steered by lower-altitude winds, and those winds were blowing east to west, straight at the U.S. East Coast. They were skirting the southern rim of a big, circular, unusually strong high-pressure center parked in the middle of the North Atlantic. High-pressure centers arise naturally, but evidence shows that some are getting stuck in place more often, a regional symptom of a warmer climate. A "blocking high" like this one had steered Hurricane Sandy on its bizarre path from the Atlantic into New Jersey in 2012.

On September 4 something unexpected happened: weak Florence moved over a spot in the west-central Atlantic that was abnormally warm. Fueled by that warmth, it rapidly intensified to a Category 4 hurricane and at a nearly record-breaking northerly latitude. Random hot pools of ocean water are another regional effect of our changing climate.

As Florence churned, the forecast models began to coalesce: it seemed likely to hit the coastal Carolinas and stall, where it could unleash deep flooding as Hurricane Harvey had done a year earlier over Houston. Sure enough, Florence struck the coastal Carolinas on September 14 and sat for four days. The low-altitude steering winds were now too weak to move the system. Florence dropped more than 30 inches of rain in places and reportedly killed more than 50 people and millions of animals (mostly chickens) while racking up an estimated $20 billion or so in losses. Floodwaters passing through factory farms, mines and sewage-treatment plants polluted rivers and estuaries for weeks.

Florence's wrath will not soon be forgotten, and neither will the blatant demonstration of climate change in action. The hurricane's unusual severity can be attributed to specific effects of climate change: greater heat in the air and ocean, extra water vapor, the tenacious blocking high and weak steering winds. These factors are in play around the world, favoring rapid storm intensification, heavier precipitation, greater flooding and stronger storm winds.

Florence was just one of many examples in 2018 of the various ways climate change is affecting extreme weather. Multiple "bomb cyclones" battered the northeastern U.S. An outbreak of Arctic air called the "beast from the east" froze Europe. Severe heat waves crippled Japan, Scandinavia and Greece. Floods ruined parts of Venice, Paris and Maryland.

Such misfortunes have happened since humans walked the earth, of course. But every year it becomes clearer that today's epidemic of bizarre weather cannot be explained by natural variability. Although in the past scientists were careful to not directly link climate change to specific weather events, we are now indeed saying that because of climate change, major floods are occurring more often. Killer heat waves are hotter and lasting longer. Cold spells are sticking around longer in some places, too.

How much of our daily wild weather, which in 2018 caused more than $160 billion in losses worldwide, can be blamed on changing climate? The answer depends on untangling the roles of three broad factors. First is the global effect of more heat in the ocean and more heat and vapor in the atmosphere. The water vapor story deserves more attention than it gets: vapor is another greenhouse gas that traps heat, it releases even more heat when

IN BRIEF

Scientists can now show that specific extreme weather events are made worse by climate change, not just natural climate variability.

Global climate change factors include more heat in the world's oceans and more heat and vapor in the atmosphere.

Regional factors include an expanding tropical zone, a "cold blob" in the Atlantic Ocean and a disrupted polar vortex; all can interact with natural variability.

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1

2

WILDFIRE burns in Kårböle, Sweden, in July 2018, magnified by abnormal heat and drought (*1*). In September 2018 a stagnant high-pressure center traps Hurricane Florence above the eastern U.S. for days, flooding towns such as Lumberton, N.C. (*2*).

it condenses into clouds, and it feeds precipitation from storms.

The second factor is regional effects, such as stubborn, blocking high-pressure centers, expanses of melting sea ice, a growing "cold blob" of ocean water south of Greenland, a slowing Gulf Stream and an increasingly disrupted polar vortex.

The third involves the complicated ways that natural variations, such as El Niño and La Niña, interact with the regional factors. Research into this interplay is cutting-edge, controversial—and bearing fruit. We now understand better how and why climate change is escalating extreme weather, revealing how we will need to prepare for increasingly frequent and intense dangers.

A NASTY NOR'EASTER

THE EARTH'S ATMOSPHERE is a cloak of roiling gases. Air constantly heats and cools, with the sun pouring in energy during the day and warm surfaces radiating it back to space at night. Uneven heating creates local winds that blow every which way. Water is continuously evaporating from land and sea, condensing in the air and falling down as rain or snow.

Yet within this chaos are remarkably predictable patterns governed by latitude, the earth's spin, mountain ranges, ocean circulations and other influences. In the Atlantic, hurricanes like Florence form in the eastern tropics and move westward. In the Pacific, tropical storms move westward, too. A polar jet stream blows the other way—from west to east—around the Northern Hemisphere at a latitude near the U.S.-Canada border; another polar jet in the Southern Hemisphere crosses the lower reaches of South America and Africa. More cyclical are large wind systems linked to ocean-temperature fluctuations, such as El Niño and La Niña, which wax and wane every three to eight years and affect winds and precipitation worldwide. Data from cores of mud extracted from various seabeds show these patterns have held for hundreds of thousands of years.

Chaos and consistency also prevail in the oceans, over longer cycles, amid constant heating, cooling and flowing waters. The Pacific Decadal Oscillation is a seesawing of warm and cold temperatures between the eastern and western North Pacific Ocean, each phase persisting for about a decade. The Atlantic Meridional Overturning Circulation is a slow current of warm, salty surface water that heads north in the western Atlantic, then loses heat, dives deep and flows back south to Antarctica. A round-trip through this circuit takes about 1,000 years.

Interactions between the atmosphere and oceans introduce natural variability into climate. Some years are hotter or colder in certain regions; some years are wetter or drier. But those same mud-core data from past millennia show that the variability has limits: the climate rarely exceeds certain bounds. Until now.

I experienced one of those exceptions firsthand in the late winter of 2018. March is supposed to roar in like a lion, but this was ridiculous. Mother Nature was delivering a parade of potent nor'easters—storms that churn just off the Atlantic Coast, lashing the Eastern Seaboard with winds from the northeast. The three climate change factors—global higher heat and water vapor, regional effects, and the interplay between natural variability and those effects—are goosing these storms.

I was anxiously monitoring the latest forecast models. They showed a seemingly innocuous wiggle in the jet stream over the North Pacific, and they agreed that it would cross to the Atlantic Seaboard and spawn a whopper of a storm aimed at our coastal town in southeastern Massachusetts. The models were bullish about a blizzard developing quickly—technically a bomb cyclone—and dumping its snow right on my neighborhood. It would be the third major nor'easter of the season, which is unusual.

All the ingredients were in place. Cold air was entrenched over Eastern states (a naturally occurring factor). Extra heat in the ocean (a global factor) provided ample energy and moisture for a mounting storm. Water temperatures in the Atlantic off New England were far above normal (a regional factor).

The interplay between natural and regional factors was another important ingredient. In late 2013 the Pacific Decadal Oscillation flipped from its so-called negative phase to a positive phase, in keeping with its natural cycle. It raised sea temperatures above average along the western coast of North America. Extra

MATS ANDERSSON *Getty Images (1);* JOE RAEDLE *Getty Images (2)*

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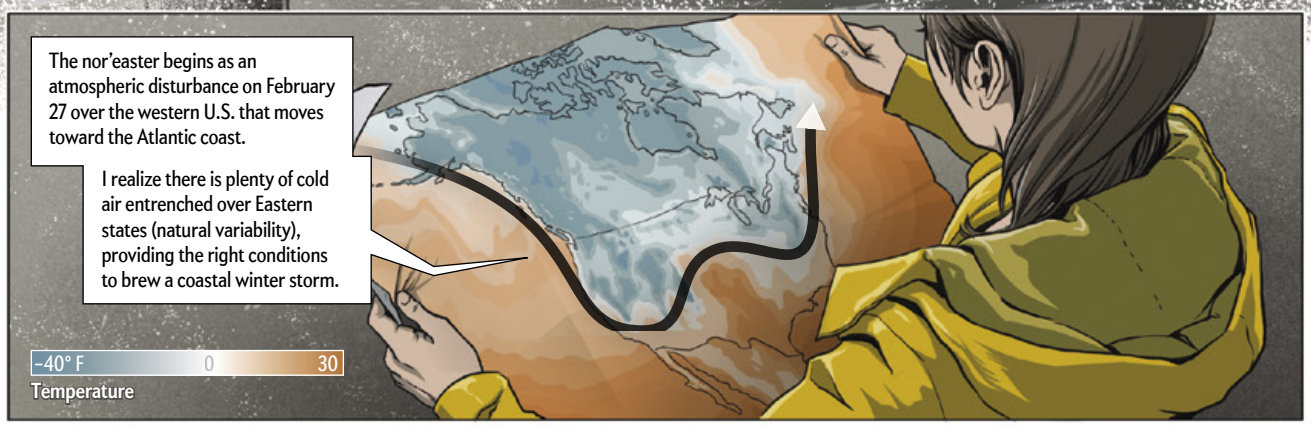
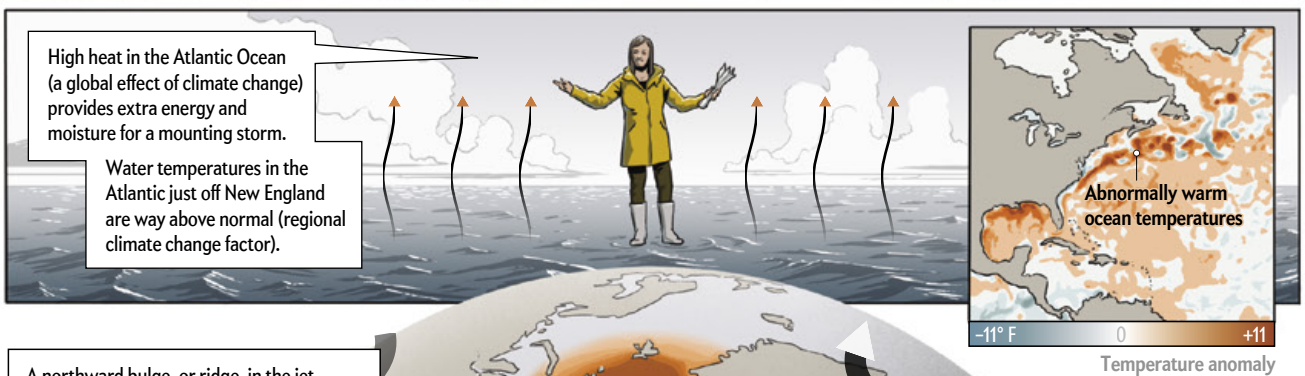
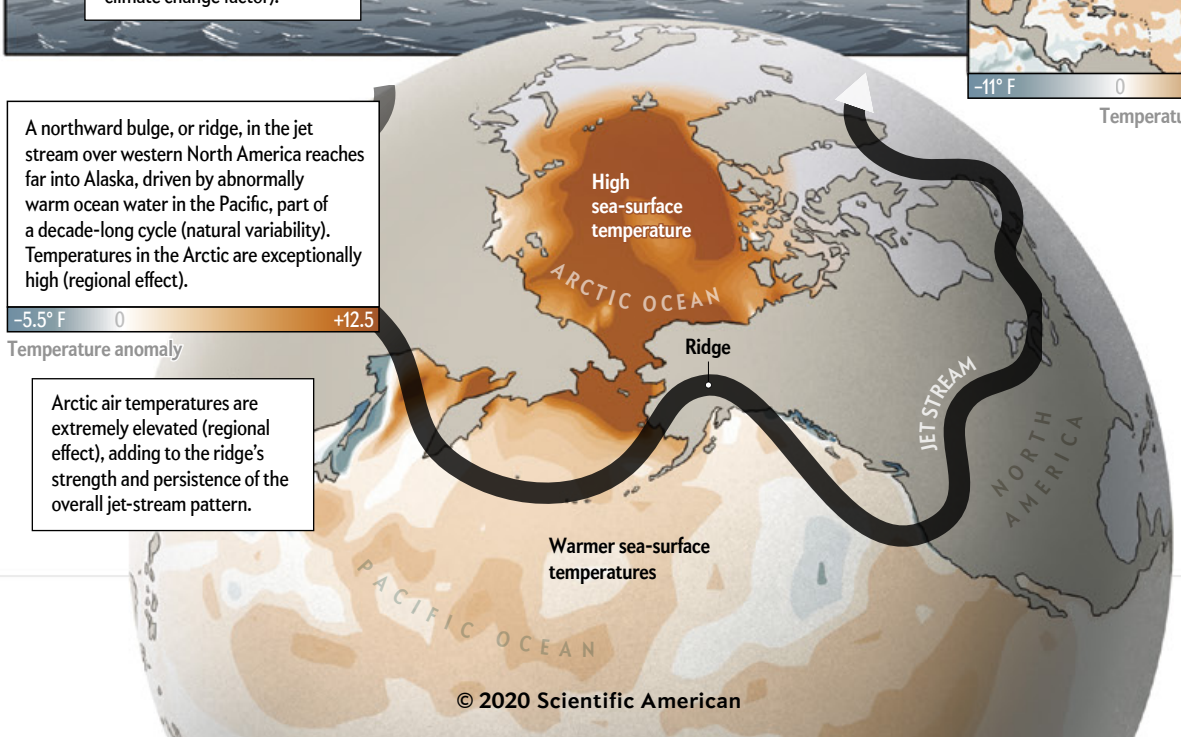
Juicing the Storm

On March 2, 2018, a nor'easter named Riley blasts the northeastern U.S., killing nine people, drowning communities under feet of snow, inches of rain and pounding ocean waves, and knocking out power to homes for two million people, including mine. Natural climate variability provides some of the storm's ingredients, but global and regional effects of climate change amplify the storm's severity. —*J.A.F.*


The nor'easter begins as an atmospheric disturbance on February 27 over the western U.S. that moves toward the Atlantic coast.
I realize there is plenty of cold air entrenched over Eastern states (natural variability), providing the right conditions to brew a coastal winter storm.
−40° F
0
30
Temperature


High heat in the Atlantic Ocean (a global effect of climate change) provides extra energy and moisture for a mounting storm.
Water temperatures in the Atlantic just off New England are way above normal (regional climate change factor).
Abnormally warm ocean temperatures
−11° F
0
+11
Temperature anomaly


A northward bulge, or ridge, in the jet stream over western North America reaches far into Alaska, driven by abnormally warm ocean water in the Pacific, part of a decade-long cycle (natural variability). Temperatures in the Arctic are exceptionally high (regional effect).
−5.5° F
0
+12.5
Temperature anomaly
Arctic air temperatures are extremely elevated (regional effect), adding to the ridge's strength and persistence of the overall jet-stream pattern.
High sea-surface temperature
ARCTIC OCEAN
Ridge
JET STREAM
NORTH AMERICA
Warmer sea-surface temperatures
PACIFIC OCEAN

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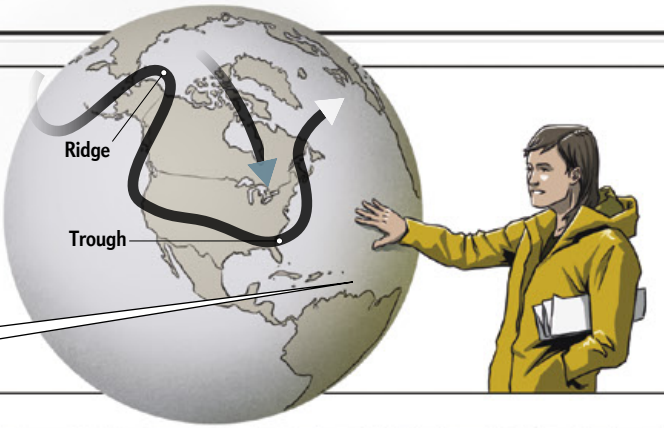
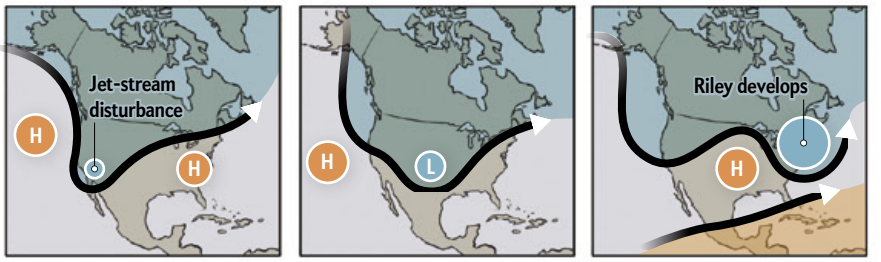
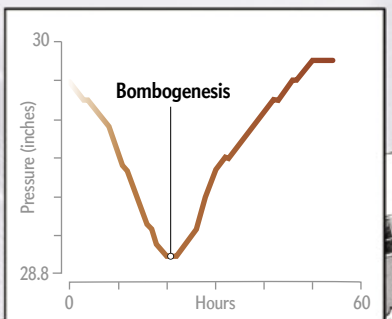
The strong ridge leads to a large southward trough that extends over most of eastern North America. It allows frigid Arctic air to plunge down, creating an abrupt temperature contrast with the warm Atlantic coast waters (regional effect).



The disturbance in the jet stream (a small wave in the larger ridge-trough pattern) moves east and flattens, but when it hits the strong air-temperature contrast along the East Coast, it strengthens again (regional effect) and picks up extra energy from a subtropical jet stream that is blowing across the southern U.S. (natural variability).





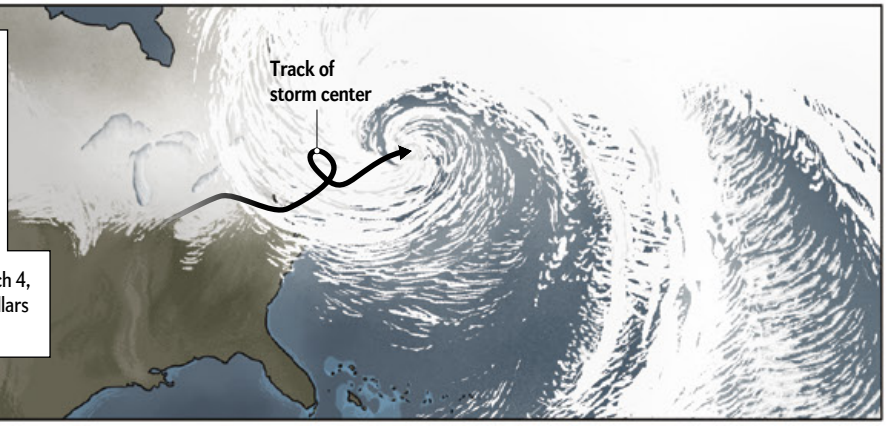
National Weather Service data for the developing storm near my location on March 1 reveal that "bombogenesis" is about to happen—when a storm's atmospheric pressure drops sharply and quickly—causing Riley to "explode" in size and strength (regional effect).

Riley's 80-mph winds lash New England on March 2, knocking down trees and power lines across a wide area. Heavy rain drenches some areas; snow falls at three inches per hour in others.

Ocean waves 15 feet high pummel houses along east-facing shores in Massachusetts.

The intense storm stalls offshore of New England for two more days instead of moving on, pumping out more wind, rain, snow and battering seas. A blocking high-pressure center near Greenland thwarts its movement—yet another regional effect of climate change that is happening more often in the North Atlantic.

Riley finally departs on March 4, leaving behind billions of dollars in damage.



SOURCES: NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (*jet stream and Pacific Ocean temperature in fourth panel, data in fifth and sixth panels and storm track in eighth panel*); UNIVERSITY OF MAINE (*temperature data in second and third panels and Arctic air temperatures in fourth panel*); NATIONAL WEATHER SERVICE (*bombogenesis graph*)

Illustration by Matt Twombly

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heat pumped into the atmosphere from this warm water favors the formation of a northward bulge (called a ridge) in the jet stream over western North America that can extend into Alaska.

That is where interaction with a regional effect comes into play. Air temperatures in the Arctic have risen two to three times faster than the rest of the planet, especially in winter. The extraordinary loss of 75 percent of the Arctic's sea-ice volume in only 40 years is responsible for most of this warming. The Pacific ridge can tap into this extra warmth, causing it to intensify and stick around for a long time. This so-called Ridiculously Resilient Ridge is largely responsible for the extended drought and heat waves that set the stage for recent severe wildfires along the U.S. West Coast.

A strong ridge is usually accompanied by a large southward dip (called a trough) to the east of it, which in this case was over eastern North America. A deep trough allows cold Arctic air to plunge far southward, creating a stark temperature contrast with the warm Atlantic waters along the East Coast. The atmosphere despises temperature contrasts. It generates storms to mix air masses in an attempt to even out the differences; bomb cyclones are an intense example of this process. This ridge-and-trough pattern tends to spawn nor'easters, and it has become increasingly prevalent in recent winters.

Sure enough, National Weather Service data painted a scenario of "bombogenesis"—when a storm's atmospheric pressure drops more than 24 millibars in 24 hours, causing it to "explode" in size and power. My neighborhood was in the crosshairs. As dusk arrived on March 2, so did the nor'easter's howling wind, driving rain and snow, power outages, and major erosion from high waves and storm surges. Afraid that one of the tall white pines in our yard might fall on the house, my cat and I (my husband was away) opted to sleep on the living-room couch rather than in my upstairs bedroom. The wind roared so loudly overnight that I did not hear the crash of any of the 20 big trees that dropped around us, somehow missing our roof.

The storm took its sweet time leaving, as a blocking high-pressure center near Greenland thwarted its movement, ravaging half a dozen states with hurricane-force winds. The nor'easter killed at least nine individuals, knocked out power for more than two million people (five days in our town) and flooded coastal communities.

WICKED WINTER WEATHER

THE PARADE of destructive nor'easters was not the only winter weather in 2018 juiced by climate change. Parisians and Venetians suffered the worst flooding in half a century as a result of prolonged rainfall, while deadly windstorms struck Germany and northern France. Several feet of snow buried Davos, Switzerland, just as the well-heeled and high-heeled tried to arrive for the annual meeting of the World Economic Forum.

In North America, the big story was "weather whiplash"—sudden and dramatic shifts between long-lasting extremes. Although research is still sparse, evidence is accumulating that these exaggerated swings are occurring more frequently and that our three climate influences are in play.

Case in point: during three weeks of January 2019, such bitter cold gripped the eastern U.S. that iguanas in southern Florida dropped from trees in near-frozen comas while residents in Western states basked in above-normal temperatures. Then in early February, weather whiplash struck. An abrupt reversal in the jet-stream pattern brought record-breaking warmth to hundreds of Eastern cities. Temperatures jumped more than 40 degrees Fahrenheit in 24 hours, bringing the iguanas back to life. At the same time, a deep chill settled over the Western states. In the atmospheric battleground between the eastern and western air masses, potent storms in the Mississippi Valley caused the worst flooding in decades. The frequency of heavy precipitation in that region has increased by about 40 percent since the 1950s.

Science is rapidly revealing that climate change can be blamed for amplifying extreme weather. Natural variability cannot explain what we already see and feel.

Global, regional and interplay factors had struck again. Overall global warming and moistening certainly gave these extremes a boost. And the same regionally loopy jet stream that would contribute to the parade of bomb cyclones had set the stage. Winter whiplash slapped the U.S. and Canada in February 2019, too; in some areas, temperatures ricocheted by 50 or 60 degrees F and wind chills by more than 100 degrees F in only a few days.

SCORCHING, SOAKING SUMMER

SUMMER 2018 also brought a smorgasbord of rough weather to the Northern Hemisphere, much of it exacerbated by climate change. While Japan, Texas and even Scandinavia baked for weeks, the U.S. Eastern Seaboard sloshed through its wettest season on record. Tenacious droughts plagued the western U.S., parts of Europe and the Middle East, contributing to a horrific spate of wildfires that cost $20 billion in California alone. Extreme summer conditions ruined crops, boosted toxic algae blooms, shut down nuclear-reactor cooling systems and triggered blackouts across four continents.

Some impacts were clearly related to the global factor. Higher average temperatures cause hotter heat waves. Extra water vapor feeds summer downpours and helps to raise nighttime temperatures by trapping additional heat near the surface. The exceptional heat plus humidity, especially at night, can be a deadly combination, making it difficult for the human body to cool itself through evaporation of sweat. Worldwide, thousands of people without air-conditioning died.

Less straightforward were climate influences on the summer jet stream—literally a "hot" research topic. What is already clear, though, is that both global and regional factors are involved in favoring an unusually wavy jet stream such as the one that engulfed Scandinavia in heat waves, drought and fire. Temperatures there from May through July in 2018 broke records going back 260 years.

What role did regional changes play? During spring and summer, warming occurs across a band of land south of Canada and Russia's Arctic coasts. Spring snow cover has been melting there ever earlier. The loss of this highly reflective surface exposes the

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underlying soil to strong spring sunshine sooner, drying it out earlier. Dry soil warms much faster than damp soil, so temperatures climb. The warm-up gives summer a head start, shifting the jet stream northward sooner than usual, allowing warm air to penetrate high latitudes.

The band of abnormally warm land can help split the jet stream into two branches, a common occurrence during winter but less so in summer. Weather systems between the two often get trapped for long periods because there is little wind there to move them along. During the summer of 2018 the jet stream over Eurasia and North America was split much of the time, creating persistently warm, dry conditions in some areas, and prolonged rainy periods in others, that broke records on both continents.

FASTEN YOUR SEAT BELT

THE WILD WEATHER OF 2018 was a trailer for the main feature, coming to audiences everywhere as greenhouse gases continue to accumulate. Some of the consequences of global effects—warmer oceans, warmer air and increased atmospheric moisture—are obvious and direct. Intense research is focused on untangling the jumble of regional effects and their interplay with natural variability. Let's look at four examples.

Evidence suggests that the earth's tropical zone around the equator has been widening toward the poles. That pushes storm tracks poleward and makes some temperate regions hotter and drier. The clearest symptoms can be seen in the dry zones that define the northern and southern edges of the tropics, such as southern California, the Mediterranean and Australia, where more severe droughts and heat waves have captured headlines. Scientists are working to understand the likely contributors—warming, atmospheric dust and soot particles that alter air temperatures and cloud formation.

Another regional factor under scrutiny is the apparent slowing of the Gulf Stream, a major ocean current flowing from the Gulf of Mexico up the Eastern Seaboard, then across the North Atlantic toward the U.K. It is the surface branch of the larger Atlantic Meridional Overturning Circulation. A slowdown would upset weather patterns and fisheries on both sides of the ocean. Measurements of the subsurface ocean are sparse, but oddities in well-monitored surface temperatures, such as abnormal warmth along the East Coast and the blob of cool waters south of Greenland, provide important clues that this large-scale circulation system may indeed be slowing. A shift in ocean-temperature patterns will alter the strength and path of storms. A hyperactive North Atlantic storm track in recent years may be a response to a slowing Gulf Stream, along with feverish waters that most likely fomented the bomb cyclones of the winter of 2018.

Blocking high-pressure centers are another regional feature to watch. Observations suggest they are occurring more often in some places, such as over Greenland and western Russia, but atmospheric models struggle to predict the development and demise of these swirling eddies in the sky. Blocks can form for various reasons, some related to natural variability and some to climate change. The remnants of tropical storms, for example, can naturally inject surges of energy into the jet stream, causing it to buckle and spin off orphan eddies. As oceans warm, however, tropical storms may survive farther northward and later into the autumn season, increasing the likelihood of collisions with the jet stream that can create a block, which can then push hurricanes and other weather systems in unusual directions.

During October 2018, for example, Hurricane Leslie dawdled in the Atlantic for more than two weeks, finally going where no known hurricane has gone before: just west of Portugal. Strong winds and flooding rains pummeled the Iberian Peninsula. At the time, a strong block sat over northeastern Europe, creating the wavy jet-stream pattern that captured Leslie and carried it on a long journey across the Atlantic.

A final regional factor is the stratospheric polar vortex, which was in the news frequently in the winter of 2018—and again in the winter of 2019. It has been behaving oddly. This ring of strong winds circles a pool of frigid air over the North Pole only in winter, at an altitude of around 30 miles. Every few years the right conditions can deform the ring or even split it into two or more smaller rings, which tend to migrate southward, bringing severe cold spells with them. Simultaneously, warm air from the south invades the Arctic, creating topsy-turvy temperatures. During the split polar vortex in late January 2019, it was warmer near the North Pole than in Chicago. These so-called sudden stratospheric warming events can occur naturally, but lately they are happening more often. Several new studies have found that the dramatic sea-ice loss in the Arctic Ocean north of western Russia may help trigger these vortex disruptions. Those of us living in the midlatitudes may be attacked more frequently by the polar vortex as global warming intensifies.

Although certain aspects of the uncontrolled experiment we are forcing on the earth's climate remain elusive, science is rapidly revealing that climate change can be blamed for amplifying extreme weather and its consequences. Understanding the links will help us see the future more clearly and prepare for the impacts on agriculture, international security, marine life, forests, freshwater resources, infrastructure and human health. The effects are already apparent and will only worsen.

Yet there is reason for hope. The rash of bad weather has shined a bright light on the well-funded campaign to spread disinformation and generate doubt about climate change among the public. Despite what the doubters say, natural variability simply cannot explain the extremes we already see and feel. Recent surveys show most people finally accept that climate change is real and caused by us. Insurers, military leaders, property developers and municipal administrators are responding to the tangible risks to life and property. Perhaps we are finally ready to confront the rough ride ahead. SA

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MORE TO EXPLORE

More-Persistent Weak Stratospheric Polar Vortex States Linked to Cold Extremes. Marlene Kretschmer et al. in *Bulletin of the American Meteorological Society,* Vol. 99, No. 1, pages 49–60; January 2018.

Observed Fingerprint of a Weakening Atlantic Ocean Overturning Circulation. L. Caesar et al. in *Nature,* Vol. 556, pages 191–196; April 12, 2018.

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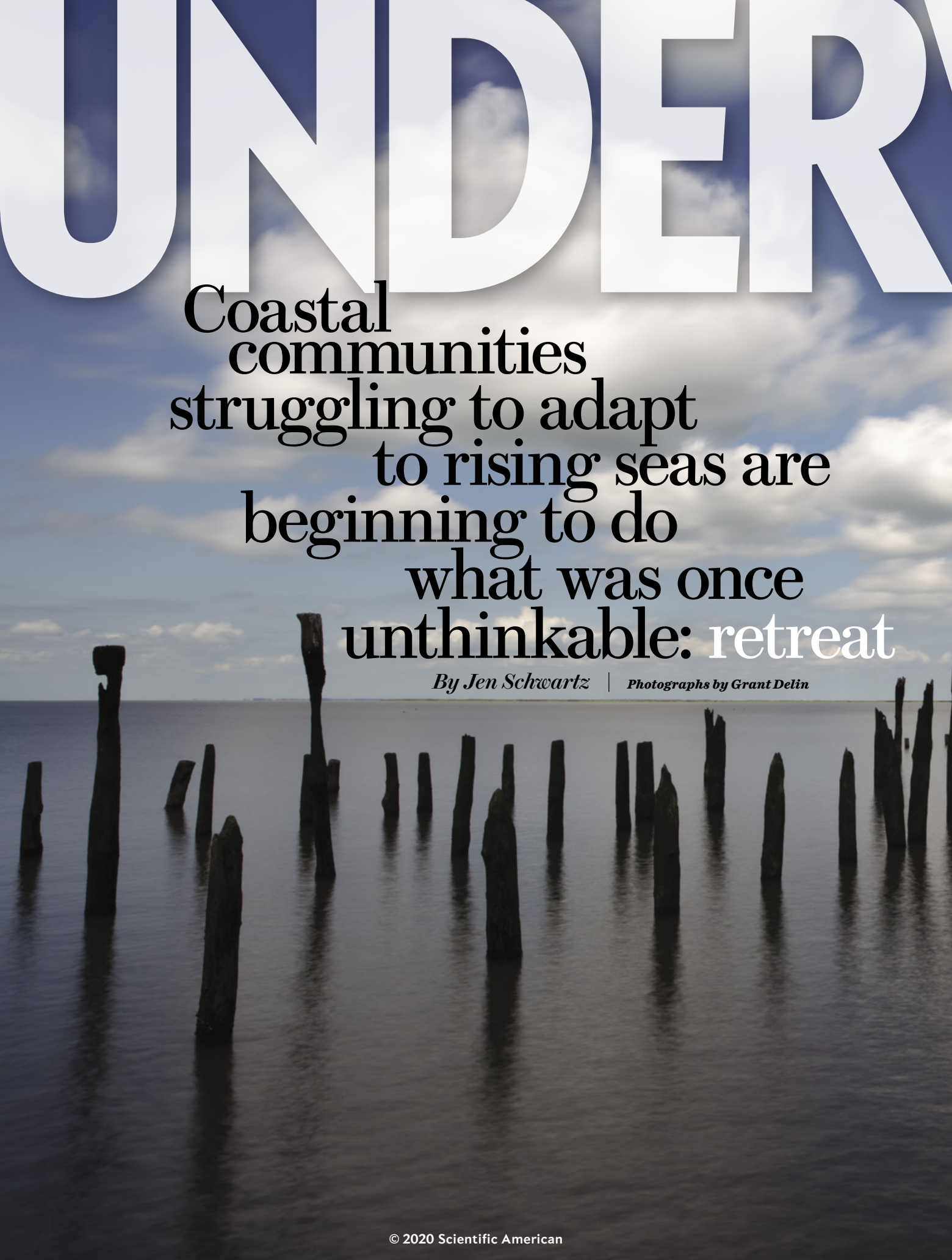

UNDER

Coastal communities struggling to adapt to rising seas are beginning to do what was once unthinkable: retreat

By Jen Schwartz | ***Photographs by Grant Delin***

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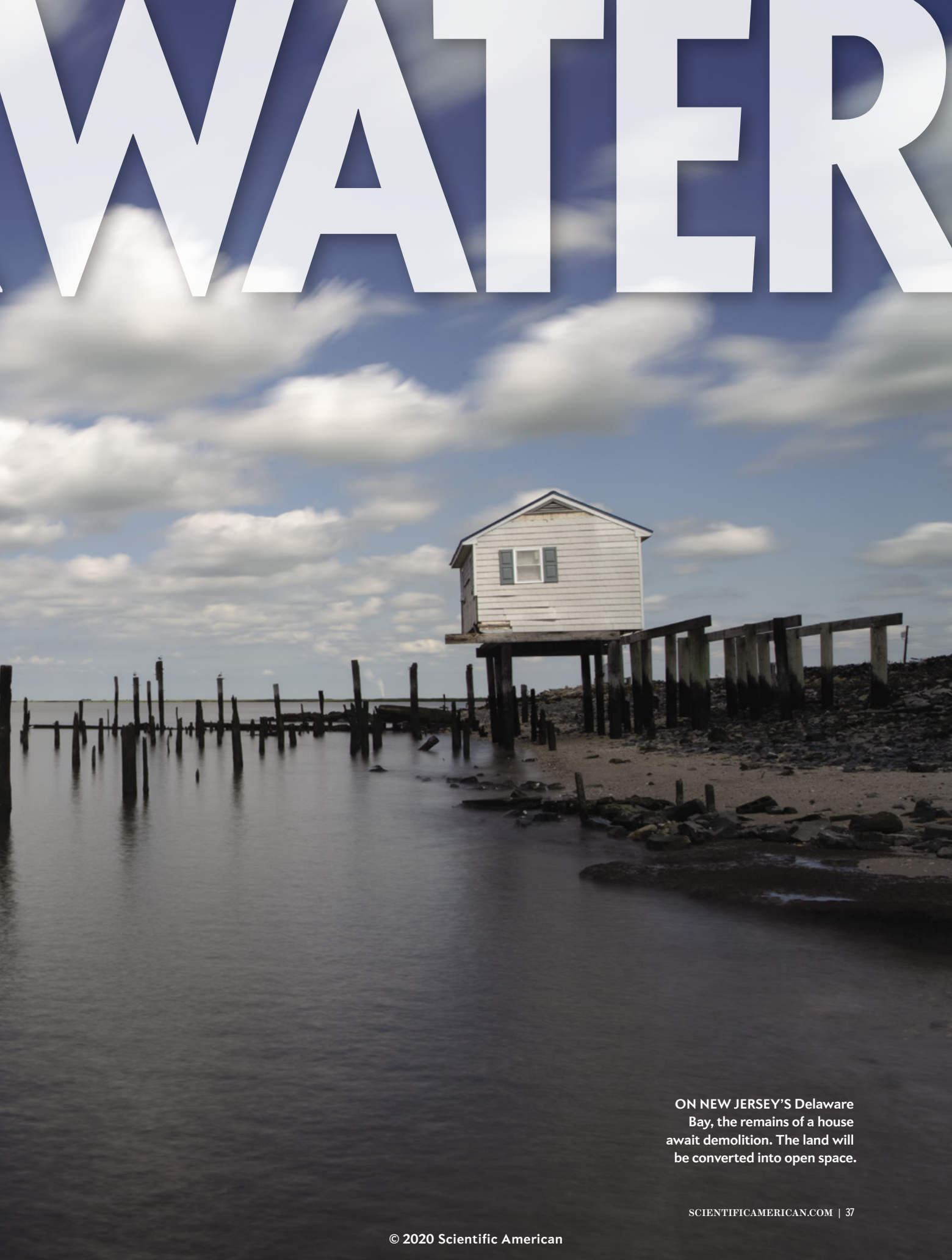
WATER



ON NEW JERSEY'S Delaware Bay, the remains of a house await demolition. The land will be converted into open space.

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MONIQUE COLEMAN'S basement was still wet with saltwater when the rallying began. Just days after Superstorm Sandy churned into the mid-Atlantic region, pushing a record-breaking surge into the country's most densely populated corridor, the governor of New Jersey promised to put the sand back on the beaches.

The "build it back stronger" sentiment never resonated with Coleman, who lived not on the state's iconic barrier islands but in a suburban tidal floodplain bisected by 12 lanes of interstate highway. Sandy was being billed as an unusual "Frankenstorm," a one-in-500-year hurricane that also dropped feet of snow well inland. But for Coleman and many residents of the Watson-Crampton neighborhood in Woodbridge Township, the disaster marked the third time their houses had been inundated by floodwaters in just three years. Taxed by the repetitive assault of hydrodynamic pressure, some foundations had collapsed.

As evacuees returned home for another round of sump pumps and mold, Coleman considered her options. Woodbridge sits in the pinched waist of New Jersey, where a network of rivers and creeks drain to the Raritan Bay and then to the Atlantic Ocean. She heard that the Army Corps of Engineers wouldn't be coming to build a berm or tide gate; the area had recently been evaluated, and such costly protections seemed unlikely. Spurred by previous storms, Coleman had already learned a bit about the ecological history of her nearly 350-year-old township. She discovered that parts of her neighborhood, like many chunks of this region, were developed atop low-lying wetlands, which had been elevated with poorly draining "fill" back around the early 20th century. As Coleman researched more deeply, a bigger picture emerged. "I started to realize that, in a sense, we were victims of a system because we were living in a neighborhood that should have never been built," she says.

Although she had flood insurance—her mortgage required it—Coleman knew that her premiums would soon go up, and she worried that her property value would go down. She and her husband liked their house, a prewar colonial. Best of all, it was affordable, a rare find in a town so close to New York City. Coleman had only discovered she would be living in a "special flood hazard area" once she was reading the closing paperwork in 2006. That made her nervous. She recalls her attorney waving it off by saying that at the rate we're going, everyone in New Jersey will live in a floodplain. That might be true in spirit, as a future-looking thought experiment, but it was severely misleading given the circumstances. Desperate to move her family away from a block in Newark with increasing drug activity, Coleman signed away one type of risk for another.

For four uneventful years, the marsh near the bottom of her street was an attractive amenity, a place where her three young sons could play freely. Then the drainages that wrapped around her neighborhood like a wishbone were overwhelmed by a nor'easter in 2010. And by Hurricane Irene in 2011. And again, by Sandy, in 2012.

When federal recovery money started trickling into New Jersey after Sandy, Coleman learned that she could apply for an elevation grant. But raising her house on stilts seemed silly if her car and the road were still on the ground. During Irene, she had witnessed what happens during a storm surge. "The high tide rushes in, and water envelops the entire area in no time at all," she says. "The street becomes a river within a river." Coleman didn't want to be "made whole," in the parlance of disaster-recovery law, if it meant rebuilding in place. Her stress levels spiked every time it rained during high tide. She didn't feel safe, physically or financially.

While commiserating with a neighbor, Coleman heard about a program called Blue Acres. Its premise struck her as radically sensible: The government would "buy out" her repeatedly flooded property at its prestorm value instead of paying to repair it yet again. Demolition crews would then knock down the house and remove other markers of human habitation. She would transfer the deed to the state, and redevelopment would be blocked, forever.

The qualifying process seemed overwhelming, compared with selling her house. But even if she could find a willing buyer, how could she ethically transfer this vulnerability to someone else? "All of us who live in high-risk flood zones were taken advantage of somewhere along the line," Coleman says. "This was a way to end that cycle."

IN BRIEF

As sea levels rise, some coastal communities are confronting a future of both chronic and extreme flooding. Retreat—permanently moving people and property away from the water—is radical, but in some places, it is inevitable.

Even well-managed retreat is messy and painful. It has rarely been tried at all. One New Jersey town is experimenting with moving a cluster of people out of harm's way and turning the newly open land into a flood buffer to protect the rest of the community.

Planning for how and when communities will need to retreat involves many variables. New Jersey could see up to 12 feet of sea-level rise by 2100. Social, political and economic factors add to the complexity.

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LAND where Monique Coleman's house stood is now planted with saplings. The house to the left will go through the same process.

RETREATING FROM THE COASTS, in concept or practice, is not popular. Why would people abandon their community, the thinking goes, unless no better alternatives remained? To emergency responders, retreat is a form of flood mitigation. To environmental advocates, it's ecological restoration. To resilience planners, it's adaptation to climate change. Everyone agrees, however, that retreat sounds like defeat. It means admitting that humans have lost and that the water has won. "American political institutions, even our national mythology, are ill-suited to the indeterminacy and elasticity of nature," wrote journalist Cornelia Dean nearly two decades ago in her book *Against the Tide*. "It would almost be un-American to concede … that it is we who must adapt to the ocean, not the other way around."

The U.S. has occasionally experimented with retreat on a tiny scale by offering voluntary buyouts to waterlogged families. The outcome is rarely promising. "Buyouts are extremely expensive, extremely disruptive, and many of the attempts have not gone well," says Craig Fugate, former administrator of the Federal Emergency Management Agency (FEMA). They invoke fear among citizens in every political stratum, bringing to mind land grabs, racist resettlement projects, class warfare, and, depending on your ideology, either federal overreach or federal abandonment. Because they require coordination among politicians, homeowners, lawyers, engineers, banks, insurers and all levels of government, they are enormously complicated to execute, even poorly. At their worst, buyouts break up community support systems, entrench inequality and leave a checkerboard of blighted lots in their wake. At their best, they avoid these things and still displace people from their homes.

Yet anyone who has looked at a map that forecasts sea-level rise can see that in low-lying neighborhoods exposed to the tides, some amount of retreat is inevitable. Regardless of how much and how quickly humans cut greenhouse gas emissions, climate change is already producing effects that cannot be reversed. Within a few decades, as saltwater begins to regularly block roads, kill wetlands, disrupt power supplies, bury popular beaches, undermine houses and turn common rainstorms into perilous floods, the most vulnerable pockets of coastal towns will become uninhabitable. As the National Oceanic and Atmospheric Administration has warned, "today's flood is tomorrow's high tide."

Buyouts, however, are not designed for adapting to climate change. Past beneficiaries were almost exclusively riverine communities in the U.S.'s rural interior—people who lived too close to the overflowing Mississippi and Red rivers, for instance, were relocated nearby. The government didn't even begin promoting buyouts as a form of disaster recovery until the 1990s, and since then, they have been conducted as one-off reactions to hurricanes. With multiple federal agencies involved, yet no one tak-

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FAWN McGEE, director of the Blue Acres Buyout Program, has purchased hundreds of houses in New Jersey, including this one. It will soon be demolished.

ing charge, "it's amazing how much we're still making this up as we go," says Alex Greer, an expert in disaster science now at the University of Albany. Until recently, retreating from the coasts was practically unheard of.

Superstorm Sandy changed that. The hurricane made sea-level rise, an abstract, future problem for far-flung places, manifest in the form of drowned subway lines and a roller coaster tossed into the waves. It communicated both the experience and evidence of future flooding in a way that probabilities never could. "It's Global Warming, Stupid," said the cover of *Bloomberg Businessweek*. Political leaders in New York State and New Jersey, sensing a tonal shift, realized they couldn't just talk about rebuilding without also talking about resiliency, the rising buzzword of disaster preparedness.

Environmental types were also acknowledging that they could no longer fixate solely on the problem of carbon emissions. Rob Moore was executive director of the Environmental Advocates of New York back in 2012. "We didn't want to talk about adaptation, because we saw it as a distraction from mitigating climate change," he says. "But Sandy made it unavoidable." A few months later Moore took a job at the Natural Resources Defense Council (NRDC) to work on how the country would cope with rising seas. Climate scientists who study the acceleration of sea-level rise felt a similar urgency, and many emerged from their silos to produce better projections. "Now the geophysical people are talking to the atmospheric people and to the economists and the sociologists," says Robert E. Kopp, director of the Institute of Earth, Ocean, and Atmospheric Sciences at Rutgers University and a lead author on major climate reports. This interdisciplinary approach has led to localized forecasting. Instead of only one number—the global mean—we now know that sea-level rise will vary significantly from region to region.

As flooding worsens, a few massive seawalls will likely be built to protect densely populated economic centers, such as lower Manhattan. But there is only so much money, and time, for cement enclosures. Residents in places such as Tangier Island in Virginia and Isle de Jean Charles in Louisiana—and globally from Bangladesh to the Maldives to Senegal—are coping with the same reality as Coleman and her neighbors in Woodbridge Township: a wall isn't coming to save them, and the floods are already here.

NEW JERSEY'S CHIEF OF LAND ACQUISITION clasps her hands on the approach to Bay Point, a peninsula that is disappearing into the Delaware Bay. This is the site of the state's first beachfront buyout, a hard-won success for Fawn McGee. Of the 31 properties she has acquired here, most were recently demolished. Some of the houses were already long gone, leaving behind skeletons of whittled pilings repurposed by nesting ospreys. "It's bittersweet," says McGee from atop a mound of makeshift riprap, residents' last-ditch attempt to stop the erosion. "Even when you can be excited that we bought all these homes, and now we're going to restore the land, everybody is miserable that they had to leave."

When it comes to the unsustainable development of the American coastline, New Jersey owns the honor of being the first and worst. It was here that the tempestuous beach environment, long

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feared and avoided until industrial times, was rebranded as a summer vacationland. Atlantic City and Cape May were tourist destinations by the mid-1800s, escapes from the undignified swelter and infectious diseases of Philadelphia. The Lenape people had long done the same—a seasonal migration to the shore—but they came to fish, not to conquer the sand with an arsenal of hotels and boardwalks. To hold everything in place, New Jersey was the first state to try to wrest control of coastal sediment flows from nature by erecting seawalls and jetties and bulkheads, and today virtually none of its coastline is untouched by human intervention. It's no surprise that the first speculator to see dollar signs on the sandbar that became Miami Beach was a New Jerseyan.

For the communities McGee works with, retreat has gone from a strategy of last resort to the only option left in the span of about a decade. Climate change drove that shift. But the reason people are in this predicament in the first place is because of the unchecked hubris of coastal engineering, coupled with general human tendencies to love the water and ignore the future. The government gave a huge boost to coastal development in 1968 by introducing the National Flood Insurance Program—an exemplar of moral hazard that allowed homeowners to rebuild over and over in risky areas while keeping their premiums artificially low. Fifty years later that program has accumulated $36.5 billion of debt while effectively trapping people who might prefer to escape to higher ground, NRDC's Moore explains.

Coastal systems, by their tidal nature, are always dynamic and occasionally volatile. The harder we tried to make them stay put, the less stable they became. In the 1960s, when scientists discovered that beaches armored with hard structures actually eroded faster and recovered slower than natural ones, the Army Corps of Engineers began dredging sand from the continental shelf and pumping it back to the shore. Before long, a storm would wash it away, and the dredging would begin anew. Today the Eastern seaboard has a Sisyphean dependence on the "nourishment" cycle. As sea-level rise rapidly accelerates, beach towns are increasingly desperate for fresh infusions of sand, which the corps must travel farther offshore to find. Geologists warn that we are running out of usable sediment faster than the planet can replace it. Wealthy homeowners in Florida are now stealing sand from public beaches to fill in their private ones.

Just as New Jersey pioneered the quixotic development of the coasts, it is leading an acceptance of what it wrought. Twenty-five years ago the state's Department of Environmental Protection (NJDEP) launched the Blue Acres Buyout Program, using state money to purchase a handful of routinely flooded houses here and there. McGee, who runs the program now, was its first leader to leverage federal money from FEMA and other agencies, turning Blue Acres into one of the country's very few standing buyout departments to deal with rising tides. Florida and Louisiana don't even have their own versions. Blue Acres, McGee says, has three major goals: permanently move people and property out of harm's way; open the land for public access; and restore the natural ecology so that the ground becomes a sponge, mitigating flood risk for the rest of the community.

After Superstorm Sandy, McGee prioritized buyout eligibility for entire clusters of houses over individual ones. In that way, the open space created would be big enough to have a real impact on managing floods. She looked for towns based on where enough homeowners had expressed interest in the process *and* the local government was willing to part with a portion of its tax base. After all, when the houses disappear, so, too, goes the tax contribution. Homeowner participation is voluntary, with an ability to pull out at any stage before signing the final contract. That means that families in a "buyout zone" will ultimately have to make a profoundly personal decision about whether or not to uproot in the context of both their neighbors' choices and their town's vision for the future.

The year before Superstorm Sandy, McGee tried pulling off her first large round of buyouts in the aftermath of Hurricane Irene. It didn't go well. "On paper, buyouts make a world of sense, but in practice, that is absolutely not true," Greer, the disaster scientist, says. McGee scrutinized how the process got disjointed and stalled out, making it nearly impossible for anyone to make decisions. It took more than a year for the funding to align, leaving desperate homeowners in a lurch. Some people were upside down on their mortgages, which disqualified them from the program. Or they couldn't afford to keep living in temporary housing while waiting for answers. As disaster amnesia began to set in, many decided just to pursue the readily available methods of rebuilding or elevating. "I realized this went way beyond land acquisition," McGee says. She tasked her tiny Blue Acres team with anticipating the adjacent challenges. "When Sandy hit and the big federal money came in, we were ready," she says.

But advocating for large buyouts of clustered properties meant McGee was pushing for something novel at a moment when New Jersey was in triage mode. The state administration wanted to recover as quickly as possible. "I think they looked at me as a troublemaker for challenging us to think beyond black-and-white," she says. McGee was arguing to disrupt the cycle of hasty rebuilding in areas where she knew the water would rise again. After many persistent meetings (her approach was "confidence, not confrontation," she says) and assurances that she could navigate through the bureaucracy, McGee convinced the state to give her plan the go-ahead.

Immediately McGee asked to borrow 33 staffers from other areas of the NJDEP. "In addition to my GIS [geographical information system] people, I brought in four paralegals, six project managers to do grant writing and deal with the feds, and eight case managers to walk families through the process," she says. "Then title people. Appraisers. Surveyors. Accountants. We had bookkeepers just to go through shoeboxes of Home Depot receipts from homeowners and cross off things like Snickers bar, water, couch." With each snag that threatened the buyouts, McGee found herself filling some unexpected role. She played a therapist to storm victims experiencing trauma, illness and divorce. When McGee saw how many homeowners were upside down on their mortgages, she facilitated short sales that amounted to more than $5.4 million of debt forgiveness—which resulted in 67 additional bought-out homes. When the issues went beyond her scope, she outsourced. "Hoarders! They literally can't get out of their houses," she says. "We had to bring in specialists to help them let go of their stuff."

Most important, McGee sensed that buyouts were a deeply communal decision. She figured neighbors would be looking at their options together over a bottle of wine, so she assigned case managers according to social groups. Case studies of buyouts show that individual considerations play only a limited role in whether a family leaves or stays. "The implication here is that residents'

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Flooding Up Close

When people think about sea-level rise (SLR), the first thing that comes to mind is the beach—narrow, sandy environments that are visibly exposed to surging water and powerful waves. Although New Jersey is known for its Atlantic coastline, much of it composed of barrier islands that are engineered to stay in place, it has a tidally influenced shoreline spread across 20 of its 21 counties. As SLR accelerates through this century, it will make tidal flooding more common and storm flooding more extreme, causing economic, environmental and social upheaval in all types of tidal communities, from bay-shore wetlands to barrier islands to suburbia. These are not problems for the next generation. According to a June 2018 report by the Union of Concerned Scientists, 250,000 homes in New Jersey, together valued at $108 billion, are at risk of chronic flooding within the next 30 years.

FROM A DISTANCE

These maps show what areas will likely be inundated by high tide at 2050 and 2100. Whether we severely cut emissions or keep polluting as usual matters little for 2050 projections; existing effects aren't reversible. (The choices we make today *will* have a big difference on how much the seas swell after 2050.) Another major factor for New Jersey is subsidence: the land itself will sink by about 0.4 feet by 2050. Relative to the baseline sea level from 2000—the average high tide from 1991 to 2009—the New Jersey coast is likely to see one to 1.8 feet of rise by 2050, according to research by Rutgers University climate scientist Robert E. Kopp and his colleagues. There is a 50 percent chance that high tide will reach or exceed the median projection of 1.4 feet above the 2000 baseline within three decades.

New Jersey Sea-Level Projections

2050

- 1.4 feet of sea-level rise (high emissions, "business as usual")

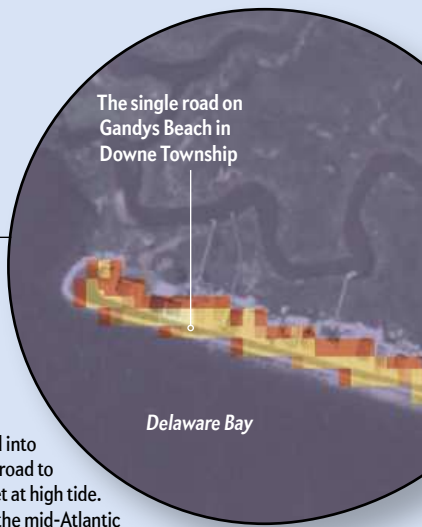
2100

- Lower emissions; more stable Antarctic
- Lower emissions; less stable Antarctic
- High emissions; more stable Antarctic
- High emissions; less stable Antarctic

New Jersey

GETTING LOCAL

Zoom in, and the range of near-future threats becomes clear. Houses will routinely flood. High tide will cut off intercoastal access roads. Popular tourist beaches and protective wetlands could disappear. And these higher water levels will be intensified by every full moon, rainstorm, nor'easter and tropical storm. "Increasingly, the research is based on compound threats of flooding instead of the single factor of sea-level rise," says Bryan Jones, a geographer who models climate migration.



BAY WETLANDS

Gandys Beach hosts a single row of homes propped up on pilings, some of which are now always over the water. In May 2018 a portion of the island's road had collapsed into the waves, and the access road to the mainland is already wet at high tide. Many coastal wetlands in the mid-Atlantic region will not likely survive an SLR rate of 0.4 inch a year, which could occur here between 2030 and 2040. Without these natural buffers, communities lose one of the most effective protections against storm surges and tidal flooding.

Map by Mapping Specialists, Graphic by Jen Christiansen

SOURCES: CLIMATE CENTRAL (*base flood maps*); "EVOLVING UNDERSTANDING OF ANTARCTIC ICE-SHEET PHYSICS AND AMBIGUITY IN PROBABILISTIC SEA-LEVEL PROJECTIONS," BY ROBERT E. KOPP ET AL., IN *EARTH'S FUTURE*, VOL. 5, NO. 12; DECEMBER 2017 (*sea-level projections*); ROBERT E. KOPP (*flood height*); U.S. DEPARTMENT OF AGRICULTURE (*base satellite imagery*)

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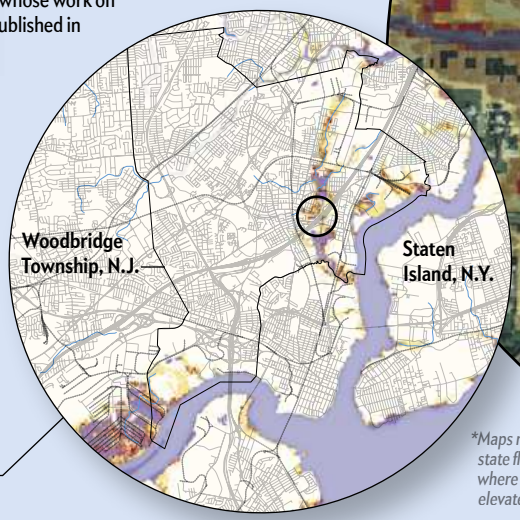
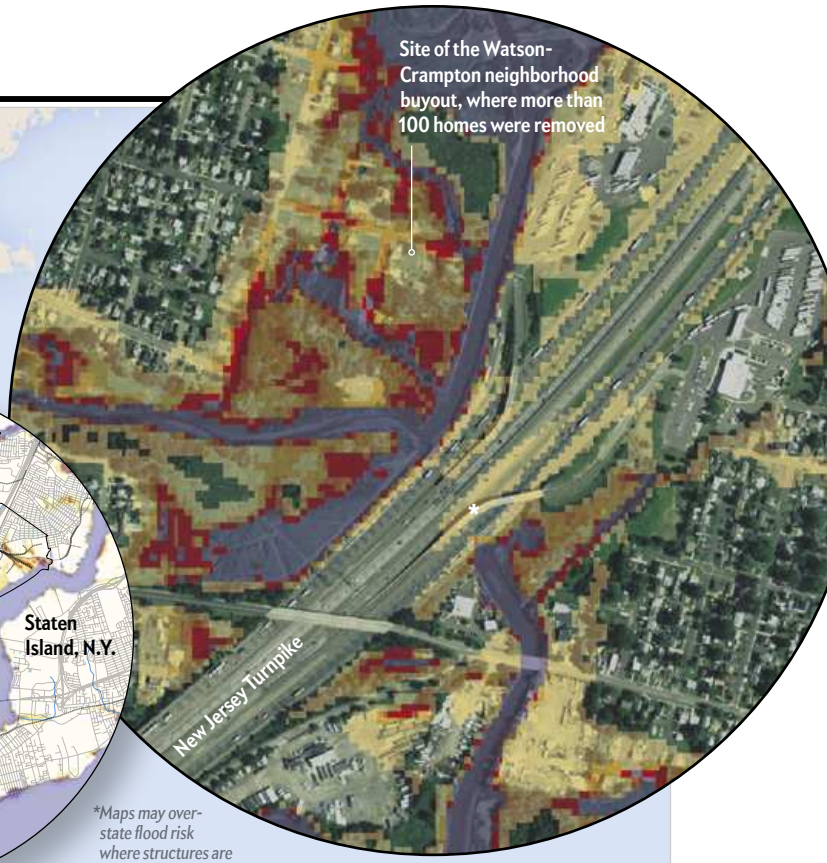
URBAN FLOODPLAIN

Dense residential areas such as Woodbridge Township are especially vulnerable as their tidal waterways swell. "When increased river discharge, precipitation and storm surges all happen at the same time, coastal regions often experience flooding that is much, much worse than just storm surge or river flooding on their own," says oceanographer Thomas Wahl, whose work on so-called compound flooding was published in 2015 in *Nature Climate Change*.

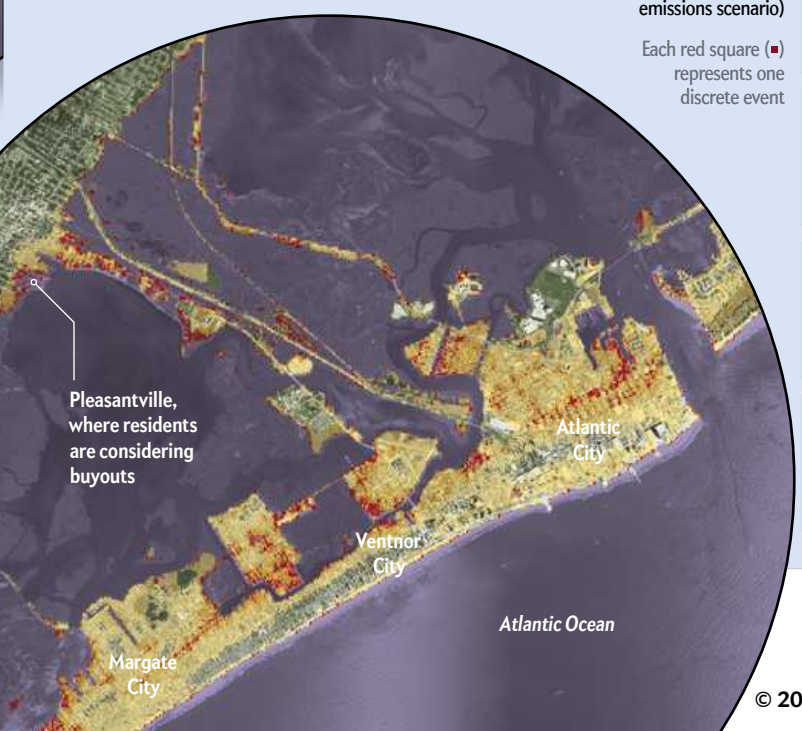




*Maps may overstate flood risk where structures are elevated above land

BARRIER ISLANDS

Long before popular beach towns such as Atlantic City, Ventnor City and Margate City (*shown below*) are permanently drowned, the effects of climate change will dismantle them in other ways. "Most people perceive the value of the beach as the sand itself," says Craig Fugate, former head of FEMA. When there is not enough space between the built environment and the water's edge to host sunbathers, will housing prices plummet? Without a sandy beach, will the town itself still have an economic raison d'être? "The question for the Jersey Shore is, Do you start thinking about giving up that first row of homes, businesses and streets in order to get the beach back?" Fugate asks. "Or will we climb up a seawall and walk directly into the water?"

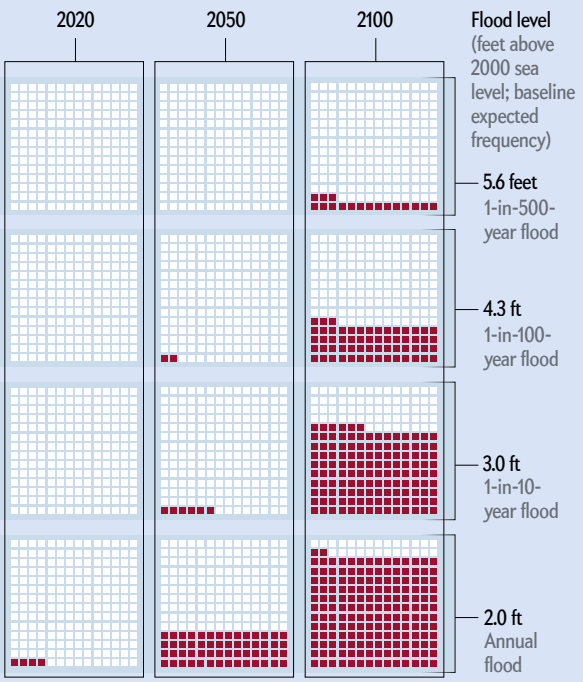


A FUTURE OF REGULAR FLOODING

The maps here show projections of how the baseline sea level will change in the future, inundating currently dry land during high tide. Just because a certain block or property isn't getting wet every day doesn't mean it will be desirable, or even possible, to live and work there. Tidal flooding, sometimes called "nuisance" or "sunny day" flooding, will occur regularly because the baseline water height is getting higher. And when storms arrive, their surges and waves will be more destructive and far-reaching. This chart shows how the frequency of flood events at a given height in Atlantic City is projected to increase as baseline sea level grows.

Expected (or average) number of projected flooding events per year in Atlantic City (high-emissions scenario)

Each red square (▪) represents one discrete event



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perceptions of their broader community were more influential in the buyout decision than were their experiences of Sandy, or their personal or family characteristics," wrote Sherri Brokopp Binder, an expert on postdisaster relocation, and her colleagues in a 2015 study in the *American Journal of Community Psychology.* McGee realized that grassroots support from a few residents could make all the difference between a transformative buyout and a dud.

IT DIDN'T TAKE LONG after Sandy for Monique Coleman to decide that she wanted a buyout. Now she would have to convince her neighbors and the town to want the same. McGee remembers meeting Coleman in 2013, when she hosted a standing-room-only meeting in Woodbridge to tell the residents about Blue Acres. "People would listen to me but then look over at Monique for her to signal it was okay," McGee says. "We always have police at these meetings because people get heated, but Monique had this calming effect on her neighbors. It was astonishing."

Coleman, it turned out, had exposure to grassroots organizing dating to her childhood. Her grandmother took her to Black Liberation Movement meetings, and her father brought her door-to-door during his city council run. These days Coleman works as a teacher for blind children, so in a sense her profession is helping others adapt to unfamiliar challenges. When Coleman and a handful of buyout supporters began canvassing their own streets in late 2012, she expected resistance. "You can't present this idea once, and when you hear that 'no,' just say, 'Okay, I understand,'" she says. She set up a blog and a Facebook group and organized monthly meetings. It was going to take a lot of listening at a time when people were traumatized by Sandy and overwhelmed by the day-to-day choices of recovery.

Blue Acres has been touted as a model for how retreat might evolve. Roy Wright, former resilience lead at FEMA, called New Jersey's approach to buyouts "masterful." But in all McGee's meetings and maps and her talks with mayors and residents, she was not able to evoke the language or data of climate change. Until January 2018, under the administration of Governor Chris Christie, McGee "was not to use those terms," as she puts it.

So Coleman took it on herself to "learn the scientific side of things." When she started doing Web searches for the impacts of climate change in 2012, she couldn't find much that spoke to her area specifically—it simply didn't exist yet. But what she did find convinced her that the back-to-back floods she had experienced in Woodbridge weren't a spate of bad luck but signals of a new reality. Coleman wrote and distributed a leaflet of 12 reasons why life in the flood zone wasn't sustainable in a climate-changed future.

Eventually some of her neighbors stopped slamming their doors when she showed up to chat about buyouts and started asking her questions instead. Coleman was patient but persistent. "It is very hard for people to accept this is really happening," she says. She explained that no matter how she sliced it, she found no positive paths forward. Leaving for good was simply the least onerous. "Who knows when a flood will come again," she would tell her neighbors. "But it will be coming."

THE MODELS SCIENTISTS HAVE MADE to predict the influence of sea-level rise on those future floods have become highly sophisticated, combining global factors such as the thermal expansion of the seas with local variables such as land subsidence and variations in the gravitational pull of land on the ocean around it. But major uncertainties remain. For one thing, we don't know how quickly and severely societies will cut greenhouse gas emissions. For the next few decades certain effects will occur regardless of how much we mitigate climate change. Rutgers's Kopp, a leading climate scientist, says that New Jersey will likely experience between one and 1.8 feet by 2050. Even at the low end, numbers like that will reshape life along the coast. After 2050 the rise continues to accelerate, but the picture gets murky: NOAA estimates that New Jersey could see between three and 12 feet of sea-level rise by 2100. That range is overwhelming if you're a mayor who is trying to come up with an adaptation strategy. "Climate change is a study of probabilities, but the public wants yes or no answers," says Graham Worthy, director of the National Center for Integrated Coastal Research.

Besides the human element, however, the biggest wild card when it comes to the fate of coastal communities in New Jersey and beyond is the stability of the West Antarctic ice sheet. The rate at which the whole of Antarctica is shedding ice has tripled over the past decade, and West Antarctica, being especially sensitive to the forces of climate change, is one of the most rapidly changing places on the planet. The West Antarctic ice sheet is so voluminous that it will add more than 10 feet of sea-level rise alone if it catastrophically collapses. This scenario might only be avoided with extreme emissions cutbacks in the next decade, according to a June 2018 report in *Nature*.

NASA's satellites have been collecting data on this ice sheet and others for more than four decades. Satellites are unrivaled at capturing continuous observations over a wide area, but they can't pick up details that would make it possible to predict the ice sheet's fate with a higher degree of certainty. Some of those more granular clues include ice thickness, the grounding line where a glacier's base meets the sea and the slope of the ice sheet, which is a driving force that sends ice from the interior of the continent to the ocean, says Kenneth Jezek, a glaciologist and retired polar researcher. Because of its sheer size and remoteness, studying West Antarctica up close is a dangerous, logistical nightmare.

One survey project, a NASA airborne mission called Operation IceBridge, has been able to capture some of those details by flying above the region in a retrofitted jetliner. From an altitude of just 1,500 feet, scientists onboard this winged laboratory can see that the top of the ice sheet is textured with signs of movement, such as geometric crevasses, the milky cerulean of ancient ice exposed to sunlight and cracked-up plains that resemble lake beds in drought. These features, they know, are carved by katabatic winds from above and by invisible rivers from below. But it is the ridges of black bedrock that hint at dramatic topography underneath the ice—a hidden world that IceBridge has been mapping extensively over the past decade.

To understand what is happening under the frozen surface, pilots maintain a precise track over the sheet while radar streams data to an onboard computer screen, revealing evidence of entire mountain ranges and valleys that make up the shape of the continent. A gravimeter picks up the depth and size of glacial cavities filled with seawater, a marker of how floating ice shelves might be melting as they interact with the ocean. Along the glaciers' terminal edges, icebergs float against the inkiness of the Amundsen Sea, a scene photographed every second by two cameras affixed to the belly of the plane. IceBridge has flown some

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AS HOUSES come down, Thomas C. Flynn, Brooke Maslo and Jeremiah Bergstrom are restoring floodplains in Woodbridge Township, N.J.

of these tracks year after year, capturing change in unprecedented detail. At a time when the necessity of earth science is being attacked by political leaders, "I can't emphasize enough that we do not collect this data because we find it scientifically interesting," says John Sonntag, IceBridge's mission scientist. "We collect it to try to warn and protect our communities from sea-level changes that are coming their way."

As raw data from IceBridge, satellites and similar projects have percolated through scientific papers and reports such as the 2017 National Climate Assessment, new tools have emerged. NOAA's Digital Coast and Climate Central's Surging Seas, for instance, allows town planners to begin envisioning how sea-level rise will affect flooding in their jurisdictions.

IceBridge data have turned out to be essential for filling in fundamental gaps in polar ice knowledge, "but we still have a way to go in Antarctica," says Eric Rignot of the University of California, Irvine, and NASA's Jet Propulsion Laboratory. Rignot was the lead author on a landmark 2014 paper in *Geophysical Research Letters* that used radar measurements of a large sector of West Antarctica and concluded that it "is undergoing a marine ice sheet instability that will significantly contribute to sea level rise in decades to centuries to come." That same week a *Science* paper suggested that, based on modeling, the collapse of the West Antarctic ice sheet had already begun, making extreme sea-level rise inevitable, possibly within two centuries. But Rignot thinks that time line might be too conservative. Real observations of ocean temperature—and how glaciers are responding to those warmer waters—are still "totally lacking" in parts of Antarctica, meaning that "it is a matter of fact that our projections tend to underestimate sea-level changes," he says.

Neither Rignot nor Jezek thinks that the NASA ice-monitoring satellites will be enough to narrow the uncertainties coming out of Antarctica. Rignot suggests that it will take more airborne research such as IceBridge, along with shipborne surveys by unmanned subs and multibeam sonars and new forms of intelligent technology—"an entire army of robotic devices"—dispatched to the remotest fringes of the continent.

Next up, science teams led by the U.S. and U.K. will travel by air and icebreaker to West Antarctica's marquee feature—the massive and infamously unstable Thwaites glacier—to do just that. More than 100 scientists from around the world will study the interaction between warming ocean water and the ice shelf to examine how Thwaites is thinning from below. Thwaites is like a tub stopper holding much of West Antarctica in place; if it's doomed, so is the ice shelf. The more these researchers and others learn about the shifting dynamics among ice, ocean water and atmosphere, the more factors they can plug into regionally specific sea-level predictions. The data they gather will inform whether coastal populations have centuries, or mere decades, to prepare for the onset of the deluge.

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TIDALLY INFLUENCED wetlands abut the Watson-Crampton neighborhood in New Jersey. By 2050 it will likely be underwater.

BY THE SUMMER OF 2014, when Coleman signed over the deed to her old house and moved into a new one, Woodbridge Township was on its way to becoming the site of Blue Acres' biggest ever buyout project. As of mid-2018, a total of 142 homeowners had accepted offers. And about 115 homes from the Watson-Crampton neighborhood alone had been removed, most of them clustered within a grid of streets covering about 30 acres. Millions of people globally will have to move inland to escape the coming floods, so these numbers can sound too tiny to be meaningful. But what happened in Woodbridge upends many of the assumptions traditionally tied to buyouts: that no residents want to leave, that politicians will never get onboard, that ecological health in suburbia will never win out over real estate growth and that no one is planning for a climate-changed future by making painful choices in the present. "What we're doing here is paving the way for conversations about how to manage retreat," says Thomas C. Flynn, the town's floodplain manager.

Officially the buyout process ends once the property has been demolished. Woodbridge, however, found itself with an abundance of lots and ambitions beyond mowing the grass. The town reached out to Rutgers ecologist Brooke Maslo, who works with the school's Cooperative Extension to assist New Jersey communities with science-based projects. The term "resilience" gets tossed around a lot, "but what does it actually translate to?" Maslo asks. She came to see the Watson-Crampton buyout project as a unique opportunity: she could create a floodplain restoration that buffered the remaining neighborhood from sea-level rise. She brought in Jeremiah Bergstrom, a landscape architect with experience managing stormwater in urban environments. "As far as I can tell, this is the first coastal land restoration in the context of residential retreat," Bergstrom says.

Using nature as infrastructure is a well-established concept—think mangroves and oyster beds as storm-surge absorption—but it is not commonly applied in places as densely developed as the greater New York City area. Liz Koslov, an assistant professor at the University of California, Los Angeles, who did ethnographic research on Staten Island's post-Sandy buyouts, says she has seen next to no discussion about what happens to the land itself after the houses come down. "Residents said they just want the land to go 'back to nature,' but when you get down to it, 'nature' can mean a lot of different things," she says. Karen O'Neill, a Rutgers sociologist who is cataloguing global instances of coastal retreat, says that "you hardly ever see a comprehensive ecological restoration. It just doesn't exist."

The Watson-Crampton neighborhood can't simply return to nature, because it was built on fill. "We have to re-create a new ecology, a new nature," Bergstrom says. Over the past year the restoration team has ripped out roads, assessed soil quality, and planted more than 950 saplings to increase flood storage capacity and encourage the growth of a biodiverse salt-marsh habitat.

Without intervention, the land would become a monoculture of invasive reeds that can break down and form dense mats, which might ultimately make flooding issues worse, Flynn explains. Maslo and her team are softening the hard curvature of the swale so that tidal surges entering from the river below the New Jersey Turnpike don't rush in at high velocity. They'll carve a channel that will allow for spillover, with the hope that the depressions will create permanent standing water for wildlife. Maslo wants to prove that a town can recoup its tax losses with new lures, such as parkland trails and a kayak launch. "This is not a wasteland," she says.

Maslo's vision helped to convince the Woodbridge mayor and city councillors to change the township's buyout regions—120 acres in all—from residential zoning and existing marshland to something they named the Open Space Conservation/Resiliency Zone. No development would be allowed. Nineteen households in the Watson-Crampton buyout area dug in their heels. The town warned these "holdouts" that if they ever wanted to sell, their houses would first need to meet new floodplain standards—which would likely mean elevating them higher. Land-use changes like this are controversial because they make what is supposed to be a voluntary process into one that is significantly less so. But without them, developers might be attracted to come in and build bigger and higher properties. Then new people—those who can afford higher flood insurance premiums and the building costs of living in a floodplain—are likely to move in, replacing those who can no longer afford to stay.

COLEMAN RELINQUISHED HER HOME to the forces of nature. Four years later, in 2018, she says she has no regrets about taking the buyout. For moving within the same county, she received an incentive grant of $10,000, which helped her afford another single-family home on higher ground. The process was financially and emotionally stressful, but the way Coleman describes her participation reframes a reaction to misfortune as a deliberate act. In an era of climate refugees who will be forcibly cast out of their homes by either too much water or not enough, Coleman sees herself as more of a retreat pioneer—someone who seized whatever agency she could as she faced an uncertain future. "There's nothing worse than sticking your head in the sand and resisting all this change going on around you," she says. "Because then you end up feeling pushed to make a decision that you are not prepared to make."

McGee, meanwhile, is playing the long game. In the spring of 2018, five and a half years after Sandy, Blue Acres was still submitting new buyout applications to the federal government. Woodbridge is on its third round of buyouts, which involves seven of the 19 holdouts that remain in the resiliency zone. "I don't close out a grant until we've done enough demolition so that the holdouts can digest how the character of their community is changing," McGee says. The tactic is working. She has spent $172 million of her total funding pot, which has grown as other recovery programs failed and FEMA directed the unused money her way. Blue Acres has facilitated nearly 1,000 buyout offers since Sandy, of which 713 have been accepted by homeowners. "You think it'd be 10,000 families for all the work we've done, but it's not, because it's so damn hard," McGee says.

Woodbridge's resiliency zone is not quite ready to be held up as a demonstration project. The work isn't done, and the marsh isn't yet beautified. Over the years, as the houses came down in stages, the scene sometimes looked like an eerie abandonment of the built environment, not a harbinger of progressive adaptation. But now that nearly all the structures are gone and the outlines of formerly paved roads are blurring into grass, "it looks less like a ghost town and more like it's just land," says Coleman, who visits every few months to see the transition in progress. "Now it's the houses that look like they don't belong."

No one disagrees that undeveloping certain areas of the coastline will be messy and expensive. But as the science of coastal resilience becomes more collaborative, the how-to of retreat may become less daunting. Retreat, after all, will not mean drawing a line some distance inland from Maine to Florida and removing everything to the east, explains Bryan Jones, a geographer who models climate-induced human migration. Modeling combined with artificial intelligence is now producing tools that allow planners to play out what-if scenarios in their towns. If, say, you buy out 40 houses from one location, restore groundwater storage and run the 100-year flood of the future, would that significantly reduce damage to adjacent houses? What are the social and economic trade-offs of undeveloping one neighborhood to protect another? Can land be designated as a safe relocation spot? These are the kinds of questions that Fugate, who led FEMA during Sandy, and others are working on now. "Just as the quantification of catastrophe risk drove a huge expansion in catastrophe insurance, it is about to drive a great industry of disaster risk reduction," wrote Robert Muir-Wood in his 2016 book *The Cure for Catastrophe.*

Retreat is so new that few planners are thinking about the next step: relocation. "Globally, there's substantial evidence that people end up right back in harm's way," Jones says. In a survey of Staten Island families who took buyouts after Superstorm Sandy, Binder, the sociologist, found that 20 percent moved to a home that is equally or more vulnerable to flood risk. As more inhabitants begin to flee slightly inland, they will encounter a wave of people still moving toward the coast. Just like backwash hitting the surf, the result could be turbulent.

As U.C.L.A.'s Koslov wrote in 2016 in *Public Culture,* "the complexity and ambivalence of retreat serves as a reminder that there are no easy solutions and that it is not possible to rebuild forever or to wall ourselves off from the problems we face." Re treat signals not just the physical movement of recalibrating to the tides but an existential reckoning with our ways of living along the water. The word itself is borrowed from the language of geologic processes, which humans have undeniably hastened. As glaciers and beaches retreat, so, too, will we. SA

Jen Schwartz is a senior editor at *Scientific American* who writes about the intersection of science and society.

MORE TO EXPLORE

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Taking Chances: The Coast after Hurricane Sandy. Edited by Karen M. O'Neill and Daniel J. Van Abs. Rutgers University Press, 2016.
The Water Will Come: Rising Seas, Sinking Cities, and the Remaking of the Civilized World. Jeff Goodell. Little, Brown, 2017.
Rising: Dispatches from the New American Shore. Elizabeth Rush. Milkweed Editions, 2018.

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LIVESTOCK ARE INJURED in January 2020 near the town of Cobargo on the southeastern coast of Australia the day after a bushfire swept through, killing animals and destroying businesses and homes.

JAMES BRICKWOOD *Getty Images*

Fueling Australia's Unprecedented Bushfires

Such an extreme fire season is at least 30 percent more likely because of global warming

By Andrea Thompson

IT WAS ONLY IN MARCH OF THIS YEAR that the massive wildfires that began tearing through the national park in January near Australia's capital city of Canberra were finally declared out. In the intervening weeks they consumed more than 80 percent of the park. This is just one example of the enormous toll taken recently by southeastern Australia's unprecedented bushfires, which collectively killed more than 30 people, destroyed nearly 6,000 structures and wiped out hundreds of millions of animals.

The flames were fanned by a rare perfect storm of conditions, including strong

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winds, prolonged drought and searing temperatures—along with a boost from climate change. Global warming has pushed up the odds of such extreme fire events occurring in southeastern Australia by at least 30 percent—and likely by much more—according to a study submitted to *Natural Hazards and Earth System Sciences*. It is the most thorough analysis to date of the role of climate change in a particular wildfire event. The examination began as the blazes were still scorching forests and blanketing cities in smoke, impacting some of the researchers involved in the work.

The analysis suggests that although events of this magnitude will remain relatively rare in the future, firefighting efforts and other disaster-response systems need to prepare for rising odds, or they risk being overwhelmed. "I hope people will see this as the study that did show there is a link between climate change and the bushfires," says co-author Geert Jan van Oldenborgh of the Royal Netherlands Meteorological Institute.

Climate scientists have increasingly been conducting what are called extreme event attribution studies to address the inevitable questions that crop up about the role of climate change in any number of weather extremes, from heat waves to floods. The World Weather Attribution consortium (WWA), a group of researchers who conducted the new research, has pioneered a way to do such analyses immediately after an event—rather than the months or years that early studies took to complete.

Wildfires are particularly tricky for such investigations because myriad factors drive them, including weather, fuel availability and ignition sources. Helping to set the stage for the recent fires were the facts that Australia had its hottest and driest year in 2019 and that large areas had been subject to drought for three years, along with highly conducive fire weather. The new WWA analysis considered the weather and climate aspects but not the ignition sources. The researchers examined trends in a risk measure called the Fire Weather Index, which includes factors such as precipitation, temperature, humidity and wind speed. They also looked at temperature and precipitation on their own, over an area of the states of New South Wales and Victoria between the Great Dividing Range mountain system and the coast.

When fires began igniting in the region during the Australian spring, 95 percent of the country had some of the highest fire index values on record, said WWA team member Sophie Lewis of the University of New South Wales during a recent press conference. There is only about a 3 percent chance of having such extreme values in any given year, the WWA researchers say. But according to their analysis, historical records show that such high fire indices are nearly four times more likely now than they were in 1900. Based on climate models that can compare worlds with and without anthropogenic warming, those indices are currently 30 percent more likely to occur than they were 120 years ago.

The team thinks the main climate driver behind the increased odds of exceptionally high fire indices is temperature. "The hot temperatures just pull the moisture out of the potential fuels," such as trees, van Oldenborgh says. The historical records indicate the chances of the exceptional heat that gripped the region during the fires are 10 times higher now, compared with the beginning of the 20th century. But the climate models used in the study suggest such events are twice as likely because of climate change.

Van Oldenborgh says the results demonstrate that these models are consistently underestimating the rise in heat extremes with warming—something that the investigators also noticed when looking at heat waves in Europe and a trend they are now working to understand in an attempt to improve projections of future heat and fire risk.

Unlike the case with temperature, the team could not find a discernible trend in the extreme dryness that contributed to the ferocity and size of the fires. Previous research has shown this dryness was caused by La Niña and other natural climate swings, which are linked to ocean temperatures and influence atmospheric circulation. During this season, those phenomena happened to align in a way that made southeastern Australia weather ripe for encouraging fires.

Taken together, the study's results show that although "natural variation was very important and will continue to be important in fueling these large fire seasons"—and although such events are likely to remain rare occurrences—climate change is making them "substantially more probable," says John Abatzoglou, a climate scientist at the University of Idaho. He was not involved in the analysis but has investigated how climate change has influenced fire risk in the western U.S.

"WE DO THE BEST SCIENTIFICALLY THOROUGH STUDY THAT WE CAN DO, AND WE HOPE THAT THIS IS INPUT FOR THE WIDER DISCUSSION ."
—GEERT JAN VAN OLDENBORGH
ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE

The new paper points to the need for governments and the disaster-response systems they have in place to take these rising risks into consideration, Abatzoglou says. He cites the example of Australia's largely local and volunteer bushfire-fighting force, which was stretched thin during the recent blazes. Insurance companies are also paying attention to this research to better understand the changing risks, he adds.

The study's authors hope that their work will help inform the reckoning over how to respond to climate change happening in Australia in the wake of the fires. "We do the best scientifically thorough study that we can do, and we hope this is input for the wider discussion," van Oldenborgh says. SA

Andrea Thompson, an associate editor at *Scientific American,* covers sustainability.

MORE TO EXPLORE

Attribution of the Australian Bushfire Risk to Anthropogenic Climate Change. Geert Jan van Oldenborgh et al. in *Natural Hazards and Earth System Sciences.* Preprint available at www.nat-hazards-earth-syst-sci-discuss.net/nhess-2020-69

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CATCHING FEVER

Climate change is accelerating the spread of disease—and making it much harder to predict outbreaks

By Lois Parshley

Photographs by Sean McDermott

IN SOUTH AFRICA, researchers are trying to understand where the Rift Valley fever virus is lurking between outbreaks.

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KOBUS STEENKAMP'S FARM SPRAWLS along a dirt road in South Africa's central plains, where the sky makes everything seem small. Steenkamp woke up here one morning after the rains in 2010 to find something strange happening with his sheep. "You could see there's blood at their backs," he recalls. All his pregnant ewes were losing their lambs.

It was every farmer's nightmare: his herd had been infected by Rift Valley fever, a mosquito-borne virus that causes abortion and death in livestock and wildlife and can be transmitted to humans. Within days, dozens of people had also been infected. Most displayed only flulike symptoms, but in some cases, the illness escalated into a severe hemorrhagic fever akin to Ebola.

A similar scene was unfolding across the region. The survival rate in adult animals is as low as 10 percent, and nearly 100 percent of infected sheep abort their pregnancies. Dead lambs and calves were left bloating in fields until the state veterinary team came to collect and incinerate the carcasses. By the time the outbreak was under control, almost 9,000 animals and 25 people had died. Neighboring countries, such as Zimbabwe and Namibia, banned South African meat, shattering the livestock industry.

Ever since the virus was first identified in 1931 in Kenya's Rift Valley, outbreaks like this one had been confined to southern and eastern Africa. But in 1977 the disease migrated north through increased trade on the Nile River, causing what the World Health Organization called an "explosive outbreak" in Egypt. Then, in September of 2000, it jumped to the Arabian Peninsula, arriving in Saudi Arabia and Yemen—sparking anxiety that Europe and North America were next. The idea that the virus could spread across these continents in just a few years is not some hyperbolic scenario. Rift is transmitted through a broader range of hosts and vectors than West Nile virus, which arrived in New York City in 1999 and spread across the U.S. in less than six years. The U.S. Department of Agriculture has taken notice, naming Rift the third most dangerous animal pathogen, behind only bird flu and foot-and-mouth disease. But health officials are not just worried about its impact on animals and agriculture. Zoonotic diseases—infectious illnesses such as the novel coronavirus causing the 2020 global pandemic, as well as Rift, that begin in animal populations and jump to humans—are the biggest risk for epidemics and pandemics. They have been responsible for some of history's worst, including bubonic plague and Ebola.

The fear of Rift growing into a global pandemic highlights that public health researchers still don't know how to effectively predict disease outbreaks, which have devastating consequences on health, economies and political stability. Meanwhile the threat of emerging zoonotic diseases is expanding—and often in unforeseen ways. Scientists are only just beginning to understand how outbreaks correlate with shifting weather patterns—a hallmark of climate change. As they do, the picture is becoming more complicated. Worldwide, temperatures are changing faster than anyone previously predicted, and as a result, habitats are, too—altering the ranges of animals, viruses and, increasingly, humans. These complex relationships are now more volatile than ever, leading one recent *Lancet* paper to conclude that climate change is "the biggest global health threat in the 21st century" and yet another in the *Lancet* to suggest that it "threatens to undermine the last half century of gains in development and global health."

Global warming and extreme weather patterns are already dramatic forces on public health. Intensified floods, droughts and storms are changing how humans can use land and, ultimately, where we can live. As climatologists race to model what has changed so that coastal communities, for instance, can adapt to rising seas, epidemiologists are also realizing how critical it is to develop epidemic-prediction tools that incorporate new and impending weather patterns. Such research is a matter of equity between developing and developed nations. And in an ever more globalized world it may be a way of averting a future of unprecedented pandemics.

AN INTERCONNECTED APPROACH

TO GET TO STEENKAMP'S FARM, biologist Ettienne Theron has been driving for hours toward an endless horizon. His truck, loaded with coolers full of blood, bounces down a crumbling highway that is flanked by open grassland. These velds are where the last several Rift epidemics in South Africa began. It's here, in an area larger than the size of Maryland, that Theron and dozens more researchers are collecting and analyzing data for a project run by EcoHealth Alliance, a global nonprofit that focuses on pandemic prevention. The challenge for scientists and policy makers alike is to learn how to intervene before pathogens infect people. Once a pandemic emerges, said EcoHealth president Peter Daszak in a 2015 video, "all you can really do is put out the fire." The goal of this five-year, multidisciplinary project is to examine, for

IN BRIEF

Researchers still cannot predict how diseases turn into epidemics. But a new approach that incorporates climate models may provide some key answers.

A rare, multidisciplinary project in South Africa is looking at Rift Valley fever to understand the volatile dynamics among weather, land use, humans and animals.

Climate change is complicating and hastening how diseases spread, with unforeseen consequences.

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the first time, exactly how climate affects Rift Valley fever in southern Africa. In doing so, researchers hope to develop a data-based model that actually predicts outbreaks before they happen, a stepping-stone to making models for other viruses as well. Notably, the U.S. Department of Defense has funded the entire project. Rift can easily be used as an aerosol and was weaponized by both the U.S. and the Soviet Union during the cold war. But bioterrorism is only one concern; keeping diseases from reaching the U.S.'s shores—and knowing how to react if they do—is increasingly a matter of national security.

Theron finally arrives at an unmarked gate, and the team members, who collectively speak nine of the languages represented in the Free State province, pile out of the truck and pull on muck boots. Using a random distribution of GPS points, the researchers have reached an agreement with 361 isolated farms like Steenkamp's, where, for two years in a row, they have taken blood samples from livestock and farm staff to test for Rift antibodies, trying to understand where the virus might be lurking when no one is reporting active cases.

Steenkamp himself was infected during an outbreak in the 1970s, and according to the WHO, as many as 10,000 people a year contract the virus. That number will most likely rise. A 2016 study published in *Emerging Microbes & Infections* reports that the "explosive nature" of recent epidemics suggests the virus has mutated into a more infectious and severe strain. As it migrates to new places, the virus may evolve further, becoming even more dangerous.

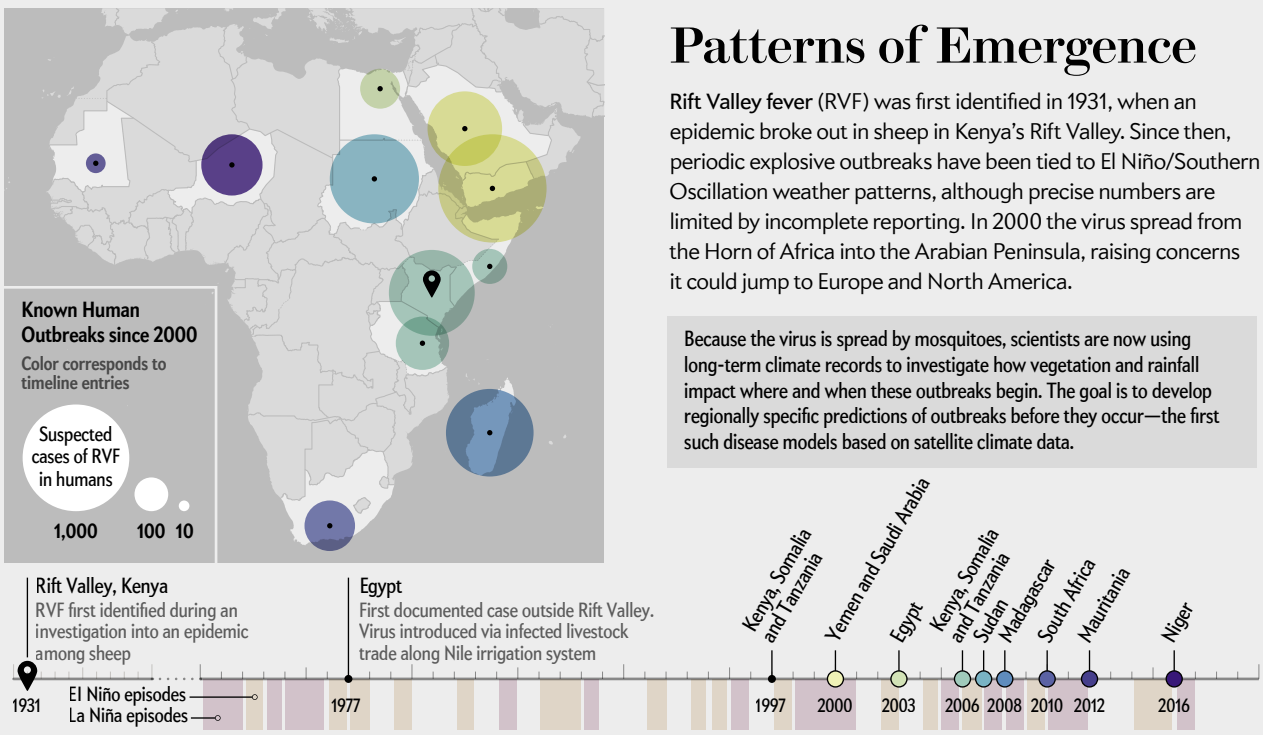
AT ONE OF 22 WEATHER STATIONS set up by the EcoHealth Alliance's Rift Valley fever project, Zikhona Gqalaqha, then a graduate student at the University of the Free State in South Africa, collects data on soil moisture.

As the farm crew maneuvers sheep into a corner of a rusted corral, field coordinator Claudia Cordel unpacks an arrangement of empty vials, data sheets, latex gloves and a sharps box on a folding card table. A farm worker grabs an ewe. It bleats while Cordel draws

Patterns of Emergence

Rift Valley fever (RVF) was first identified in 1931, when an epidemic broke out in sheep in Kenya's Rift Valley. Since then, periodic explosive outbreaks have been tied to El Niño/Southern Oscillation weather patterns, although precise numbers are limited by incomplete reporting. In 2000 the virus spread from the Horn of Africa into the Arabian Peninsula, raising concerns it could jump to Europe and North America.

Because the virus is spread by mosquitoes, scientists are now using long-term climate records to investigate how vegetation and rainfall impact where and when these outbreaks begin. The goal is to develop regionally specific predictions of outbreaks before they occur—the first such disease models based on satellite climate data.



SOURCES: WORLD HEALTH ORGANIZATION AND CENTERS FOR DISEASE CONTROL AND PREVENTION (*outbreak data*); NATIONAL WEATHER SERVICE (*El Niño and La Niña data*)

Graphic by Tiffany Farrant-Gonzalez

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blood from its jerking neck. In South Africa, *Aedes mcintoshi* mosquitoes are thought to be the main carrier of Rift. The females transmit the virus directly to offspring, and their eggs can survive years of drought—a typical occurrence in this region. When the new generation of infected mosquitoes eventually hatch, they transmit the virus to livestock and wildlife alike. The virus amplifies in these hosts, so that when wider-ranging mosquitoes, such as *Culex* and *Anopheles,* bite infected animals, the original outbreak transforms into a swift-moving epidemic.

In another corral, Cordel wipes a cow's anus before piercing its tail vein. The cow lows and lets loose a squirt of green liquid toward her face. Cordel explains that though the basics of the virus transmission are known, "we have no idea how wildlife impacts people or livestock, or vice versa," adding that the feedback cycles are completely undocumented. That's why the EcoHealth team wants to get a more granular look at the interactions of weather, plants, insects, animals and people. At 22 research sites around the Free State and Northern Cape provinces, researchers trapped mosquitoes to search for the virus, studying soil composition and vegetation and setting up mini weather stations to monitor local conditions in conjunction with satellite data. This kind of comprehensive approach, which required dozens of experts in epidemiology, ecology, climatology, veterinary medicine and entomology, is both costly and relatively rare. But it may be the future of understanding how infectious diseases emerge and spread.

MOSQUITOES CAN LIVE IN AN AREA THE SIZE OF A SUBURBAN BACKYARD, SO REMOTELY SENSED DATA DO NOT GET AT THE SCALE WITH WHICH PATHOGENS INTERACT WITH THEIR HOSTS.

"It makes sense that the health of an animal population is related to the health of the human population," says Melinda Rostal, one of the project's investigators. Animals often serve as early-warning signs of a new outbreak; in 2017 in Brazil, for example, local monkey populations were nearly wiped out eight months before a yellow fever epidemic. But structuring research around interactions among people, animals and the environment has only recently gained traction in the global health community. This strategy, first defined by epidemiologist Calvin Schwabe in 1964 and now called "One Health," is an increasingly popular intellectual framework for epidemiology. As far back as 400 B.C., Hippocrates understood that the environment—including weather—impacts disease, but systematically bringing together multidisciplinary research to better understand complex systems is relatively new. The Centers for Disease Control and Prevention did not establish a One Health office until 2009, when officials acknowledged that changing environmental interactions "have led to the emergence and reemergence of many diseases." Pursuing One Health research is expensive up front, but in the long run, it can actually be more efficient: by sending out collaborative teams instead of funding individual research trips, the EcoHealth Rift project reduced the cost of transportation for its study by 35 percent.

The longtime absence of this style of coordination is partly why the global health community is still playing catchup on emerging diseases. Consider Zika, for example: although it was first identified in Uganda in 1947, it was largely ignored until it began tearing through the Americas in 2015. Such diseases often lack attention when they first emerge because they affect the poorest populations of the world, meaning they are generally not profitable for pharmaceutical development. The result is that these so-called neglected tropical diseases, according to the CDC, have already cost 57 million years of life lost prematurely. So as one of the largest One Health projects to date, EcoHealth's Rift work is an important case study: Can broad, multidisciplinary research projects fill this dangerous knowledge gap?

As the setting sun turns the grass gold, Cordel and Theron finish the farm visit by checking on a weather station, where a lonely wind propeller ticks above barbed wire. Satellite data from NASA suggests that this region will see altered weather patterns, changing its risk of both Rift and other infectious diseases. Transmission is a complicated thing, but undoubtedly a key factor in future disease control will be understanding the implications of our changing climate.

FORECASTING CLIMATE ON A BACKYARD SCALE

ON THE LONG DRIVES between field sites, dead sunflowers droop under a relentless sky. South Africa has been in a drought for a few years, and the red soil has frazzled into puzzle pieces. Drought itself is a standard feature of El Niño weather patterns, and when La Niña eventually comes and completes the cycle, the area will see heavy rains. But these cycles, while typical, are intensifying because of climate change, becoming drier and wetter, explains Assaf Anyamba, a research scientist at NASA's Goddard Space Flight Center. (In March 2018 South Africa declared a

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"national state of disaster" over its prolonged drought. Cape Town was at risk of running out of water during the worst drought in 400 years.) Even as conditions grow more extreme, Anyamba says, the downpour associated with this rain pattern—known as the El Niño/Southern Oscillation (ENSO)—and the vegetable life that downpour creates are what makes it possible to predict the hatching of Rift-infected mosquitoes. In fact, Anyamba was able to successfully predict the 2006 and 2007 Rift outbreak in East Africa by adding satellite climate models to the mix instead of just relying on regional weather patterns. "To my knowledge," he says, "this is the only system of its kind for any disease."

With that promising model in hand, Anyamba looked to southern Africa and the Arabian Peninsula. If he could apply the tools he used in eastern Africa to predict Rift outbreaks elsewhere, perhaps he could expand the model to other diseases. But so far his Rift models have failed in South Africa. As the climate expert on the EcoHealth study, Anyamba is now trying to figure out why. Satellite data that show and forecast global weather patterns make it easier to predict changes with vegetation and insects. The downside is that this big-picture view is fairly imprecise. When researchers combine climate models with more granular regional data such as vegetation coverage, they are dealing with two different scales. Anyamba's eastern African satellite models relied on a vegetation index, for example, that did not reflect southern African plant species. Other factors that impact disease, such as the spread of vectors, can be even finer-grained. Many mosquitoes live in an area the size of a suburban backyard, so even remotely sensed data do not get at the scale with which pathogens interact with their hosts. Although weather has long been linked with disease—think "flu season"—it is this level of specificity that makes predicting outbreaks so challenging. A one-size-fits-all template will not work.

Anyamba's new tactic is to use the information the EcoHealth team gathers on mosquitoes and vegetation in South Africa to build a more customized prediction model for the region. Climate change may eventually make the Free State province drier, which would help prevent Rift outbreaks. Other parts of the country, however, will likely get warmer and wetter, increasing Rift and the other diseases that floods tend to foster. Learning how to build more regionally sensitive tools will help scientists understand how disease burdens may change, both locally and globally.

Getting there is a matter of urgency. While it is rare to find sweeping conclusions in epidemiology, it is clear that greater climate variability—and therefore greater disease fluctuation—is already here. The first conclusive evidence of the trend was likely initially reported in a 2002 study published in the *Proceedings of the National Academy of Sciences USA,* which looked at cholera prevalence in Bangladesh over a 70-year period and found that "warming trends over the last century are affecting human disease." Mosquito and other insect habitats have expanded because of warming, exposing new populations to viruses. Preliminary research shows that malaria, for example, is globally on the rise. A temperature bump of just two degrees Celsius—a mark we are quickly approaching—would expand the number of people at risk of malaria by several hundred million, according to the WHO. Strangely, places that are now ideal climates for malaria may see less of it as they warm; prevalence will likely occur where malaria hasn't yet arrived, such as the U.S.

This type of vexing nuance has troubling consequences. Take bluetongue virus, a highly lethal ruminant disease that is spread by biting midges called *Culicoides.* Historically it was confined to tropical regions, but by 2006 there was enough warming in western Europe that some of those midges moved north and infected animals. Scientists were surprised when another kind of midge then picked up the virus from sickened sheep and carried it all the way to Norway. Corrie Brown, a veterinary pathologist at the University of Georgia, says bluetongue is a prime example of how climate change introduces species to one another for the first time—expanding how diseases can spread in an unpredictable manner.

Experts disagree on the best way to handle these risks. The U.S. Agency for International Development supports a strategy that focuses on identifying new pathogens, but Brown thinks merely discovering new viruses is an inefficient use of limited research funding. "I can see how very good it'd be for the investigators because they'd get a lot of papers published," Brown says, but she is bearish on its value in preventing people from getting sick. Instead Brown and others who advocate for a One Health approach think strengthening local infrastructure—building monitoring and surveillance systems and training community nurses, for instance—is the most effective way to grapple with the fickle burdens of emerging diseases. "If we improve the level of expertise of health care professionals all around the world, we'll be in a better place," she says.

Local detection systems are especially important in places where humans are the ones who have moved into new environments, exposing themselves to diseases they haven't yet encountered. "In an unchanging world, you don't see a lot of emerging disease," says William Karesh, an epidemiologist and the Rift study's principal investigator. "It's when systems alter that microbes reveal themselves in new ways." Often epidemics and their ripple effects "happen at the edge, where humans are living next to wild spaces," says Carrie La Jeunesse, a former AAAS Congressional Science & Technology Policy Fellow who worked on Ebola. Since 2009 USAID has developed a heat map for emerging diseases with pandemic potential; it is remarkably similar to maps of regions threatened by human impact. In a 2012 paper published in the

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Lancet, Karesh and his colleagues summarized these findings by explaining that "many zoonoses can be linked to large-scale changes in land use."

That is certainly true in South Africa. "We actually farm with arboviruses," the viruses transmitted by arthropods such as ticks, says Alan Kemp, an entomologist on the EcoHealth project. "With Rift, it's almost certain that thanks to cattle breeding and importing exotic breeds that aren't resistant, we're actually literally farming Rift." He sighs and says, "To be honest, to a large extent, we're guilty of our own demise."

THE HUMAN STRAIN

THE THOUSANDS of blood samples EcoHealth has procured end up under the fluorescent gleam of a biosafety level–four laboratory in Johannesburg. Like Ebola, work with Rift is allowed only in the highest level of containment, and investigator Janusz Paweska wears a pressurized protective suit to examine Rift specimens under a microscope. "Some scientists refer to nature as the most terrible bioterrorist, which I dislike," says Paweska from his office, after he has been through the elaborate decontamination process. As head of South Africa's Center for Emerging Zoonotic and Parasitic Diseases, he does not mince words: "Who creates this environment for emergence? You can't accuse nature. Uncontrolled urbanization, climate change, poverty—that's not nature. The answer is that *we* create the situation for the emergence of many of these diseases."

Arguably poverty is already the greatest risk factor for getting sick. "The major trigger or determinant of health is economic," says Antoine Flahault, director of the Institute of Global Health in Geneva, explaining that an unequal distribution of health care is the primary problem. The WHO estimates that in low-income countries, diseases of poverty that are often preventable or treatable (think diarrhea, malnutrition and parasitic infections) account for 45 percent of deaths. Climate change is expected to drive at least 122 million people into extreme poverty in the next few decades, forcing many to leave their homes and leading to rapid urbanization, all of which tends to foster disease. Flahault expects that one of the major disease contributions of climate change will come from these consequences of forced migration. "We can expect a huge impact on health, not just because of direct impact on disease but because of the indirect economic impacts, which may be very severe," Flahault says.

But when countries with limited resources are asked to prepare for a future potential threat, often at the cost of immediate problems, "it's a hard trade-off," explains Susan Scribner, director of the Preparedness & Response project at the global development firm DAI. "What we do is called health, but in some ways, a lot of it has to do with good governance," she says. That is why projects such as the Rift study could be particularly powerful: they provide data to many different stakeholders spanning agriculture, health and defense.

Anyamba, EcoHealth's climate expert, sees the Rift study as the way of the future. "I envision more projects involving climate data, fused with advanced analytics and machine-learning technologies, that will begin to answer some questions [about] why particular disease outbreaks occur," he says. Policy makers may be juggling other priorities, but it is important that they understand this science, Scribner says, "because when a pandemic hits, scientists aren't the ones in charge of the response." In fact, the DOD's Defense Threat Reduction Agency funded similarly comprehensive research to predict and map areas at risk for chikungunya, another mosquito-borne viral infection. There is a long list of diseases, such as yellow fever, dengue and even rabies, that would benefit from the kind of resources the DOD can bring to bear.

But funding—and the politics that go into deciding whose research gets it—plays a critical role in which diseases are deemed worthy of attention. In the current political climate, support for the long-term resources that logistically complex projects (such as the Rift study) require is actively disappearing. Just as we are beginning to realize how urgent a collaborative approach to disease might be, the CDC has faced massive threats to its global health security efforts. Funding global health is a complex endeavor managed by multiple agencies in the U.S. alone. Experts

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FIELD TEAM MEMBERS take blood samples from farm workers and livestock to test for Rift Valley fever antibodies. Researchers are trying to understand how the virus is maintained between outbreaks.

at the Brookings Institution think tank have written that it could be "devastating for global health," damaging economic growth as well as weakening international stability.

But the importance of doing this kind of intensive fieldwork continues. Amid this limbo, EcoHealth's sweeping fieldwork presses on. Early one morning during their collection process, the team pulls up to a private game reserve near Mokala National Park to chase down kudu, a type of African antelope. Wildlife can both carry and transmit Rift to livestock and humans, but their blood samples are especially tricky to obtain. A helicopter arrives to lend a hand. Soon trucks are bouncing over the grass, a cloud of dust marking progress toward the herd. Beyond the front tires, the animals swerve and leap. They gleam like ribbons. The stillness when one is tranquilized from the sky is shocking. The scientists work quickly, sliding around a maze of arms and legs with syringes and vials. The kudu will wake in a matter of minutes.

After the blood is collected, the researchers begin their decontamination procedures, scrubbing dust off their boots to avoid spreading any diseases to the next property they visit. Nearby, a caged lion lounges in a puddle of sunshine, awaiting the delivery of his next meal. He yawns at the stream of passing cars. Once this bushveld stretched wild over half of the country, but today it has been largely partitioned off and contained behind tall fences. There are few places now where wildlife is still able to wander free. The world has already changed, even if we do not yet know the consequences. SA

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MORE TO EXPLORE

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PREVENTING TOMORROW'S CLIMATE WARS

The U.S. military is taking steps to limit the chance that worsening droughts, rising seas and melting Arctic ice will hasten uprisings that threaten national interests

By Andrew Holland

IN BRIEF

Climate change is accelerating instability in certain regions and multiplying threats in others. The American military is taking action to prevent consequences that could endanger U.S. interests. **In Africa,** the military is trying to lessen conflicts arising from extended drought and loss of farmland. In the Asia-Pacific region, it is helping small nations recover from severe storms so they can remain strong to resist Chinese assertiveness. In the Arctic, it is promoting international laws that would limit Russia from claiming resources and shipping routes. **It is unclear** whether the military will commit enough money to sustain such operations. And there is a danger that politicians who dismiss climate change might end support.

Photograph by The Voorhes

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DEMOCRATS AND REPUBLICANS MAY OFTEN BE AT ODDS OVER climate change, but the U.S. military is not waiting for the debate to be settled. It is preparing for a hotter world, which is already altering geopolitical relations and could lead to armed conflict.

The U.S. Department of Defense breaks the menace into two parts: a direct threat to its infrastructure (think naval bases that face rising seas) and the indirect threats posed around the world if societies become destabilized. Although the first danger is relatively easy to prepare for–figure out what is vulnerable, then strengthen the infrastructure or move away from the danger—it is already proving costly and difficult to prioritize. In 2018 and 2019 the military faced nearly $10 billion in damage to its bases from climate-related impacts: Hurricane Florence caused $4 billion in damage to Marine Corps bases in North Carolina, Hurricane Michael caused $4.7 billion in damage when it leveled Tyndall Air Force Base, and Midwest flooding caused $1 billion in damage to Offutt Air Force Base in Nebraska. In just one year, three bases suffered more damage from climate-related threats than enemy action has caused in the past 60 years.

Although climate change will drive costs to infrastructure, the second threat—how it is driving global conflict—is altogether more complicated. Weather, governments and societies are complex systems, so predicting how each will react to higher temperatures is difficult. Yet credible voices have found clear links; a 2015 study published in the *Proceedings of the National Academy of Sciences USA,* for example, noted that climate change fueled the beginning of Syria's civil war by making a regional drought deeper and longer. That drought, when combined with the government's refusal to deal with crop failures and livestock deaths, pushed hundreds of thousands of people to migrate from their farms into cities such as Aleppo and Raqqa. Once protests began in the country in early 2011, many people with little to lose and resentment toward the government joined in. The unrest turned to civil war when the Syrian government started shooting protesters, and that civil war allowed ISIS, also known as the Islamic State of Iraq and Syria, to rise, terrorizing the world.

The U.S. military does not explicitly say that climate change will directly cause wars, but it does call it an "accelerant of instability" or a "threat multiplier." Such language appeared in the DOD's formal 2014 Quadrennial Defense Review, its major planning document for the next four years. It also kicks off the department's 2014 Climate Change Adaptation Roadmap, a strategic analysis of how to begin to tackle climate threats.

The Trump administration, which will withdraw the U.S. from the Paris Agreement on climate change and has rescinded as many environmental regulations as it can, has tried to take away the military's explicit focus on climate change. The 2018 National Defense Strategy, for instance, includes no mention of "climate change," and a 2017 executive order rescinded Obama-era initiatives to assess and plan for the risks of climate change. When questioned in Congress, however, senior civilian and military leadership have affirmed the security threats of climate change and recommitted the military to planning for it—given that the military must plan for reality, respond to disasters and prevent humanitarian crises from sliding into conflict.

The military has not suddenly become an arm of the Peace Corps. Its mission is to safeguard U.S. interests around the world. Protecting human lives can prevent struggling countries from becoming failed states. Recent history has shown that failed states, such as Afghanistan and Syria, present real threats to U.S. national security by destabilizing regions and breeding terrorists who could threaten Americans.

The U.S. military assesses security around the world, but there are three hotspots where climate change could lead to new conflicts—sub-Saharan Africa, the Asia-Pacific region and the Arctic. A fourth theater, the Middle East, could also be on the list, but the multiple challenges of ongoing wars in Syria, Yemen and Afghanistan have precluded longer-term thinking about climate threats.

AFRICA: DROUGHT AND TERRORISM

GEOGRAPHERS OFTEN JUDGE Africa as the continent most vulnerable to unrest in response to climate change because poverty is widespread, much of the population relies on rain-fed subsistence agriculture, climate variations can be extreme and governance in numerous nations is poor. Disease outbreaks, crop failures, persistent ethnic and religious rivalries, and corruption abound. The continent's population is expected to grow rapidly

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THREATS: Drought weakened Nigeria, bolstering terrorist group Boko Haram, which kidnapped 276 schoolgirls (*1*). Destructive storms, such as Super Typhoon Haiyan in the Philippines (*2*), can compromise a Pacific nation's ability to stand up to Chinese assertiveness. Dwindling Arctic sea ice allows Russian ships to control more territory (*3*).

DAN KITWOOD *Getty Images (1)*; KEVIN FRAYER *Getty Images (2)*; HANNES RADA *Getty Images (3)*

from 1.2 billion today to double that, or more, by 2050. Adding the stresses of climate change to this already dangerous brew, it is thought, could accelerate the existing threats and tip fragile states toward war.

In fact, it already has. In northern Nigeria deforestation, overgrazing and increased heat from global warming have turned what was once productive farmland and savanna into an extension of the Sahara Desert. Lake Chad has lost more than 90 percent of its original size from drought, mismanagement and waste. Together these factors, along with a Nigerian government that was perceived as unresponsive, led the local population into poverty and prompted migrations to find sustenance and safety.

The violent Islamist insurgent group Boko Haram stepped into the miserable vacuum left by these factors. Though originally focused on northern Nigeria, in March 2015 the group pledged allegiance to ISIS, demonstrating a clear threat to U.S. allies and interests. A chain of causation from climate change to desertification, to food insecurity, to migration and then to conflict fueled Boko Haram's rise.

The main mission of the U.S. military's Africa Command (AFRICOM) is to contain existing threats such as Boko Haram and to prevent new ones from starting. (AFRICOM is one of six combat commands based on geography that the U.S. military has formed to cover the globe. Although the Joint Chiefs of Staff and the secretary of defense give direction, each command plans most of its operations.)

Scientists know that warming in Africa will lead to more extreme weather and less water availability, which will lead to lower food productivity in places that already struggle with food security. Warmer temperatures are also allowing mosquitoes to expand their range, increasing disease transmission. Those trends, in turn, could cause more poverty and migration, which could lead to local conflicts over increasingly scarce resources, thereby undermining the stability of states and leading to violent uprisings that could rear terrorists. The military's intent is to cut this chain of causation early enough to prevent a war from starting.

One primary strategy is to help build accountable governments and government institutions, nationally and locally. To do that, the military has to know which countries are most vulnerable to climate-related conflicts and then devote resources to strengthening them.

To that end, the DOD funded a 2014 study by the University of Texas at Austin's Climate Change and African Political Stability program. It identified the most vulnerable regions of the continent. Researchers produced granular maps that overlaid climate and other security threats, showing "hot zones" where conflict would be most likely.

One particular zone was the small Central African state of Burundi. Sure enough, in early 2015 a conflict began there when President Pierre Nkurunziza sought a third term in office, even though the constitution limited him to two. Protests and an attempted coup d'état killed roughly 500 people and displaced at least 250,000 more. A cocktail of factors—including climate change—made conflict in an already unstable country more likely. But a full-scale civil war did not erupt, because the Burundian military stayed neutral throughout the crisis. And that neutrality was a testament to the American military, which trained, equipped and reformed the Burundian armed forces over the course of a decade.

Because the U.S. military does not have many boots on the ground or fleets of ships around Africa, AFRICOM's leaders see their role as a hybrid "civil-military" command that works with other parts of the U.S. government, such as the U.S. Agency for International Development, to prop up military and government

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institutions in African countries. It is ironic that one of the best ways to prevent climate change from sparking conflict has nothing to do with environmental measures.

THE PACIFIC: STORMY SEAS

THERE IS NO SHORTAGE of American military power in the Pacific, and the country is shifting even more of its overall might into this region. The new military focus on "great power competition" is clearly targeted toward a rising China. The U.S. Pacific Command (PACOM) has more than enough traditional military threats to care about, including nuclear blackmail in North Korea, maritime disputes in the South and East China Seas, tensions over the political status of Taiwan and the rising military power of China. Climate change adds two main, overlapping threats to people in the Pacific: more frequent and intense storms caused by warmer oceans, accompanied by rising sea levels. Together these developments could threaten the existence of small island states such as the Marshall Islands, Tuvalu or Micronesia. Sea-level rise could inundate key food-growing regions such as the Mekong River Delta, and storm surges are threatening the long-term viability of major population centers such as Shanghai, Jakarta, Manila and Bangkok.

In 2018 eight out of the 10 deadliest natural disasters occurred in the Asia-Pacific region, according to the United Nations.

The military's overall aim is to maintain peace, freedom of trade and international law. Meeting those goals in this economically growing region is challenging. Of special concern to U.S. military leaders is China's rapidly expanding naval strength and assertiveness there, which, if uncontested, could allow China to control the area's seas. More than half of the world's trade by ship passes through the South China Sea alone, where China is building military bases on islands it has annexed and physically expanded. The Philippines and other nations claim territory or rights to some of these islands, but Chinese leaders say the land belongs to them.

Climate change factors into the U.S. strategy to build alliances in the region. In cases of natural disasters such as typhoons, which are getting stronger because of climate change, the U.S. Navy is often the only force with the logistical experience to arrive quickly, with enough people and materials, to make a difference immediately after any destruction. China's navy does not have the capability, and the country rarely provides aid to Pacific nations following calamities. The U.S. has solidified alliances with countries around the Pacific by intervening at their hour of maximum need.

A dramatic example occurred in November 2013. Super Typhoon Haiyan hit the Philippines with winds of 195 miles per hour. The storm drove water inland at 46 feet above sea level in some places. More than 7,000 people died, making Haiyan the deadliest typhoon in Philippine history. Immediately after the storm people became desperate for aid. Credible reports came in that the New People's Army, an armed wing of the Communist Party of the Philippines, was attacking government convoys of relief supplies going to remote areas. In the city of Tacloban, eight people were killed, and more than 100,000 sacks of rice were looted from a government warehouse. Society was unraveling.

In response, then Secretary of Defense Chuck Hagel ordered the USS *George Washington*'s battle group, which was on a port visit to Hong Kong, "to make best speed" to the Philippines. Once the aircraft carrier arrived, 13,000 soldiers, sailors, airmen and marines provided food, freshwater and supplies. Their presence stopped the street violence, severing the chain between climate change and conflict.

Less than six months later President Barack Obama visited Manila to sign a new Enhanced Defense Cooperation Agreement that would deepen the alliance between the U.S. and the Philippines. Certainly a big motivation for signing this treaty was to counter China's assertiveness in claiming and occupying islands in the South China Sea. But the quick U.S. response to Haiyan reminded the Philippine government and people, who historically had been skeptical of American military engagement, why it was important to have the U.S. Navy on their side.

Extreme weather can worsen poverty, leading to uprisings that can destabilize nations, allowing terrorists to expand. The U.S. intends to cut this chain of causation.

Cementing alliances is crucial to U.S. efforts to counter China in Asia. Admiral Samuel Locklear, the recently retired commander of PACOM, said in 2013 that climate change could "cripple the security environment" in the Pacific by destabilizing the region. If an American ally always fears the next typhoon, it is unlikely to invest in the naval forces necessary to deal with traditional security threats, such as the territorial expansion of a rising power.

PACOM activities now include annual events such as the high-level Pacific Environmental Security Forum, coordinating military and civilian communications networks and helping to connect and train military personal, civilian aid workers, local governments and the U.N. The American armed forces are also helping to train Pacific militaries to fight and defeat an enemy, in part through exercises with names such as RIMPAC, Cobra Gold and Balikitan. The teams practice amphibious assaults, major naval actions and combined air defense. These multilateral exercises now also include a simulated humanitarian-assistance mission.

THE ARCTIC: OPEN TO AGGRESSION

U.S. ENGAGEMENT in the Arctic is different. The Arctic is warming faster than anywhere else on earth. In less than a decade the territory has undergone a fundamental change in state, from an ocean world enclosed in ice to one open to human exploitation. Sea ice has diminished so extensively that both the Northern

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Sea Route over Russia and the Northwest Passage over Canada are now open to travel and energy exploration for many months out of the year. Indeed, the rapid melting of Arctic sea ice in 2007 was one of the catalysts prompting the military to think about climate security implications because the U.S. Navy would have a new ocean to patrol. Ironically, though, the military's preparation for the security consequences of climate change in this part of the world seems surprisingly weak.

The Arctic falls under the U.S. Northern Command (NORTHCOM), but the European Command (EUCOM) also plays a role because it is responsible for any military action involving Russia, which is the preeminent military power in the Arctic. In many ways, the commands face a traditional suite of security challenges: rivalries among great powers, overlapping claims to resources and disputes over freedom of navigation.

A global rush is on to secure the oil and gas that the U.S. Geological Survey says sit underneath the ocean. Shipping companies are hurrying to build Arctic-capable ships that can transit over the top of the world. And countries as far from the Arctic as Singapore and India are pushing to join the Arctic Council, an intergovernmental organization of the eight countries that border or hold Arctic territory, to ensure their interests are represented. The DOD and each branch of the military have released Arctic planning documents focused on using multinational resources to improve cooperation. At a 2019 Arctic Council meeting in Finland, however, the Trump administration signaled a move to a more confrontational approach in the Arctic to counter Chinese and Russian activities. This approach has not yet been matched with new resources.

On paper, the international rule of law in the Arctic is strong; claims to territory in the Arctic Sea are governed by the U.N. Convention on the Law of the Sea (although the U.S. Senate has never ratified it). The Arctic Council is widening its influence by bringing in new observer states (which cannot vote or propose policies) such as China, Italy, Japan and India.

The power of institutions can only go so far, however. In the Arctic, the U.S. Navy faces a competitor with more resources and ambition: the Russian Northern Fleet. Headquartered in Severomorsk off the Barents Sea, the fleet is the country's largest naval operation and conducts regular exercises. It controls the biggest icebreaker fleet on the globe and currently is constructing what will be the world's foremost nuclear-powered icebreaker.

In what are apparently direct orders from President Vladimir Putin, Russia's military has created a Joint Strategic Command North dedicated to protecting the nation's interests in the Arctic Circle. The command has reopened cold war bases across Russia's Arctic coastline, including one at Wrangel Island, only 300 miles from Alaska. Long-range bombers that could test American and Canadian air defenses in the Arctic are being upgraded. And it is worth noting that Putin has continued to display a disregard for borders and international rules, flouting the global condemnation and sanctions brought on by his invasion of Ukraine in 2014.

China, too, has shown a growing interest in the Arctic, sending its two Snow Dragon icebreakers there on highly publicized tours to small communities in Iceland, Greenland and Canada.

In response to such moves by its great power rivals, the American military has begun to train surface vessels for operations in the unique environment of the High North, including a 2019 NATO exercise with an aircraft carrier above the Arctic Circle for the first time since the cold war.

This strategy is being tested as both Russia and China make very public maneuvers in the Arctic, however. To counter them, the U.S. could also show a greater "presence" with port visits to Iceland and exercises with NATO allies. History has shown time and again that when a powerful nation expands to claim more land, more sea or more natural resources, if other powers do not push back the expansion continues until a border war erupts.

Even so, NORTHCOM is reluctant to expand its Arctic presence, in part because of resources. It has said that operations in the Arctic would be extremely costly. As it stands, the U.S. Navy does not have the infrastructure, the ships or the political ambition to sustain surface operations there. The coast guard has only two icebreakers, and one of them, the Polar Star, is 40 years old. (Icebreakers are needed, even as sea ice retreats, because they provide year-round access and because ice flows are unpredictable and could trap ordinary ships.) In the 2020 defense budget, Congress approved new funding for the first new icebreaker in decades: construction has started, and it will enter service in 2023.

DOES THE PRESIDENCY MATTER?

IT TOOK A LONG TIME for foreign policy and national security experts to persuade the U.S. military to prepare for a changing climate. That's why it may surprise many that climate action within the military has continued, even under a skeptical Trump administration. The issue of climate change remains frustratingly political, with many Republicans dismissing it altogether.

Perhaps the more telling question is whether the military will be able to devote enough money to climate-related efforts, given competing priorities. The Arctic approach is not encouraging. The main source of funding for civilian-assistance operations by the DOD is the Overseas Humanitarian, Disaster and Civic Aid program, but its annual appropriation has declined to about $100 million even though the mission has been expanding.

Ultimately the truth always wins: the climate is changing, and the military commands will have to deal with its effects. It is certainly better to plan in advance for possible threats than to respond after the fact. Right now the military will not suffer a sneak attack from climate change—two of the six commands, at least, are starting to face the threat head-on. Whether that is enough to continue to cut the chain from climate change to conflict is uncertain. SA

Andrew Holland is director of studies and senior fellow for energy and climate at the American Security Project, a nonpartisan national security think tank. He has worked on the security threats of climate change since 2007 and has testified before Congress about the U.S.'s future in the Arctic.

MORE TO EXPLORE

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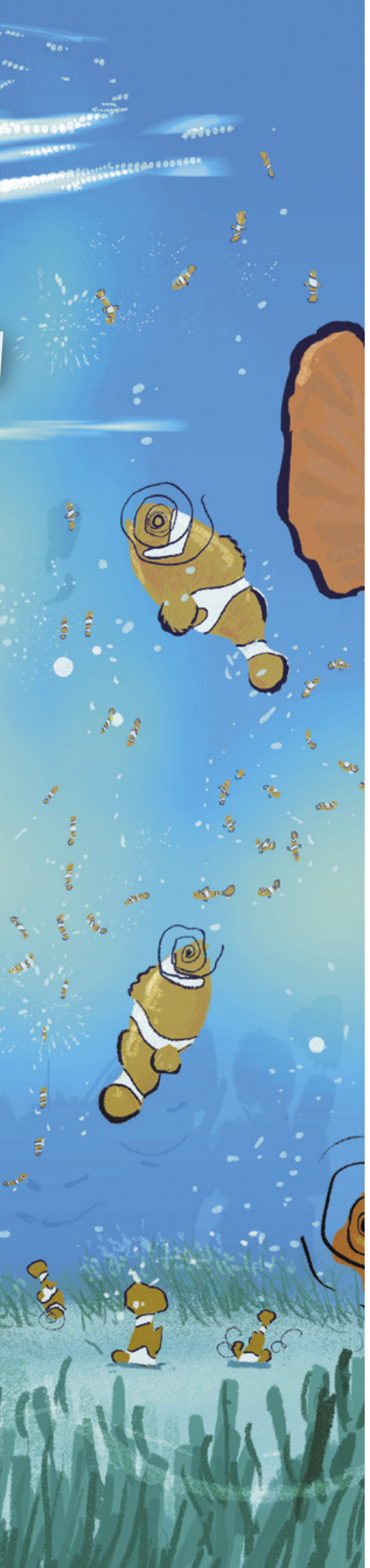

Ocean acidification may alter the behaviors of underwater creatures in disastrous ways

By Danielle L. Dixson

CLOWN FISHES LIVE THEIR ENTIRE ADULT lives nestled in the protective arms of a single sea anemone on a coral reef. Between birth and adulthood, however, the fishes have to complete a treacherous journey. After hatching, a larva—a tiny, partially formed version of an adult fish—swims out of the reef to the open Pacific to finish developing, presumably away from predators. After maturing for 11 to 14 days, the juvenile is ready to swim back to the reef and select an anemone to call home. But as it swims close, it has to cross a "wall of mouths"—all kinds of creatures, such as wrasses and lionfish, that lurk along the reef ready to gobble up the tiny fish. Most successfully navigate the gauntlet by recognizing the smells of the predators and avoiding their grasp.

The sense of smell is really chemistry in action: detecting, understanding and responding to molecules in the water. Even a small shift in ocean chemistry could throw off this delicate survival mechanism. Scientists began to wonder what might happen when the water becomes more acidic, a trend that is occurring worldwide as the oceans absorb ever more carbon dioxide from the atmosphere. In 2010 my colleagues and I put 300 recently hatched clown fish larvae in a seawater tank in our laboratory and monitored them for 11 days. When we injected the scent of a friendly fish, they did not react. But when we injected the scent of a predator (a rock cod), they swam away.

We then repeated the experiment with 300 new hatchlings from the same parents, but this time the water was more acidic—adjusted to a level we can expect in certain parts of the world's oceans by 2100 if current trends continue. The young fishes developed normally, yet not one avoided the predator odor. In fact, they preferred to swim toward the dangerous smell rather than plain seawater. When we introduced predator and nonpredator odors simultaneously, the fishes seemed unable to make up their minds, spending equal time swimming toward one smell and the other. They were able to sense chemical signals but were unable to recognize the *meaning* of the signals. The reversal of behavior was surprising and concerning. We thought that acidification might affect the chemical signaling slightly but never enough to prompt a fish to swim toward imminent death.

Creatures everywhere have three basic tasks in their lifetime: find food, reproduce and avoid becoming food in the process. In places such as coral reefs, where predators and prey densely pack a limited, complex habitat, natural selection strongly favors species that evade predators. Any disruption to this ability could have catastrophic consequences for the entire ecosystem.

If increasingly acidic water interferes with a clown fish's sense of smell, it might also interfere with other senses and behaviors. And although we studied only one species of clown fish, smell is critical for a

Illustration by Pascal Campion

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vast array of marine organisms. At a minimum, confusion and disorientation could place yet another stressor on fish already challenged by rising water temperatures, overfishing and changing food supplies. Further, if many ocean dwellers start to behave strangely, entire food webs, migration patterns and ecosystems could come crashing down. Although the science is still new, the results appear to be lining up: ocean acidification is messing with fish's minds.

THE ACID CHALLENGE

SINCE THE INDUSTRIAL REVOLUTION the atmospheric concentration of carbon dioxide has risen from 280 parts per million (ppm) to just more than 400 ppm today. That number would be much higher without oceans, which absorb 30 to 40 percent of the CO_2 sent into our air. More CO_2 in seawater causes chemical reactions that increase acidity—measured as lower pH. Surface waters are roughly 30 percent more acidic today than in the late 1800s, and if current carbon emissions trends continue to the end of the century, they could be nearly 150 percent more acidic than back then.

Additional CO_2 in the water column breaks down calcite and aragonite—two minerals that are essential building blocks of the shells and exterior skeletons of certain sea creatures. Shellfish, urchins and plankton raised by other researchers in tanks with water that had high CO_2 levels developed incomplete or deformed shells and exoskeletons. Yet scientists thought that fish and other nonshelled organisms might escape the wrath of ocean acidification, in part because early research done in the 1980s showed that certain animals had an astonishing ability to regulate their internal chemistry by increasing or decreasing the amounts of bicarbonate and chlorine in their body. These studies, however, looked only at physiology—whether an animal could survive acidified water. Maintaining normal functions such as finding food and avoiding danger is a different challenge. Our research group was among the first to tackle the next logical question: Could acidification change behavior?

CONFUSING SMELLS AND SOUNDS

OUR CLOWN FISH EXPERIMENTS strongly suggested that acidification was indeed altering the animals' behavior. Other tests since then have been equally troubling. Because many reef predators commonly feed during the day, juvenile clown fishes that are returning to a reef to find an anemone tend to approach at night, when the predators are sluggish or sleeping, preferably under low moonlight. But navigation for a fish smaller than a dime in a dark, relatively featureless open ocean is not easy, so they use sounds produced by the reef and its inhabitants for guidance. A year after our smell experiment, we looked at whether acidifying water might interfere with hearing as well.

We tested young clown fishes by putting them inside a box in a tank filled with seawater. When we pumped in daytime reef noise (which they would naturally avoid) through one side of the box, the fishes spent almost three quarters of their time near the opposing wall, away from the sound source. But when we tested new fishes that had spent their brief lives in water that was 60 percent more acidic—a level we can expect in shallow oceans by 2030—they were not nearly as wary. More than half were actually attracted to the daytime sound.

We repeated the experiment twice more, with water that was 100 percent more acidic and 150 percent more acidic—levels that might arise by 2050 and 2100, respectively. In both situations, the clown fishes spent around 60 percent of their time near the speaker playing daytime reef noise. We also ran separate tests to make sure none of them lacked a sense of hearing (they did not). Under the high acidity conditions, the clown fishes were unable to recognize the meaning of auditory signals.

Ocean dwellers that have skewed senses may not avoid predators well. But the opposite effect could also occur: they might not be able to find food effectively.

Sharks have an infamously keen sense of smell, which they rely on to navigate, locate mates and track prey. Given the sensory confusion we found in clown fishes, we wondered how sharks might react to acidified waters. We collected 24 adult smooth dogfishes—small sharks that migrate in temperate waters between the Carolinas and southern New England—from the coast near Woods Hole, Mass. We split them into three groups and held each group in round swimming pools. The sharks in group 1 simply swam around in water taken from the ocean near Woods Hole. We put group 2 sharks in water treated to mimic ocean acidity in 2050 and group 3 sharks in water simulated for 2100. Meanwhile we created a concentrated "squid rinse" by soaking squid in seawater and straining the water through a cheesecloth. (Sharks love squid.)

After five days we let each shark swim in a flume tank 10 meters long and two meters wide. The acidity matched that of the pool in which they had been held. The flume tank had two nozzles that each pushed a mild plume of water from front to back. One plume flowed along the left side of the tank, and the other plume did so along the right. After the sharks started swimming, we infused some of the squid water through one of the nozzles. We later reversed the plumes in case the sharks had a natural preference to swim along one side.

Overhead cameras and tracking software recorded what happened next. Sharks in group 1—regular seawater—spent over 60 percent of their time swimming in the plume that smelled like their lunchtime squid. Sharks in group 2 did the same. But sharks in group 3 actively avoided the scent of prey, spending less than 15 percent of their time in the squid-treated water. We saw other differences. Group 1 sharks repeatedly bumped and bit at a brick held in front of the nozzle emitting the squid water. They hit it more than twice as many times as the sharks in group 2 and more than three times as often as sharks in group 3.

It is surprising to see a predator lose interest in, and even avoid the smell of, its food. Reef fishes tested in other experiments seem to exhibit similarly odd be-

IN BRIEF

Increasingly acidic ocean water created by climate change might be undermining important behaviors that sea creatures need for survival.
Experiments show that damselfishes, sharks and crabs raised in or exposed to highly acidic water may fail to smell predators or to find food or may uncharacteristically wander into dangerous places.
It is unclear whether ocean dwellers can adapt to increasing acidity if the rise is slow or if they can pass along adaptive traits to their offspring. Tests at volcanic reefs that are naturally more acidic might provide some answers.

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havior. Given the importance of sharks as top predators to ecosystems and their known vulnerability to environmental changes, ocean acidification could be a major threat to these animals and the ecosystems where they live.

BOLD IS BAD

IT IS ALWAYS TRICKY to say that behaviors seen in a lab would also be seen in the wild. So we went to a sandy lagoon near one of the Great Barrier Reef's northern islands to examine another trait: boldness. There we tested how wild-caught juvenile damselfishes would react to predator smells after exposing them to acidic water for four days. In a flume tank, about half of them held in water with acidity expected by 2050 were attracted to a predator plume and half were not, but 100 percent of them held in water anticipated by 2100 were attracted to the predator odor.

We tattooed the damselfishes so we could identify them and then let them loose on a small reef we made in the lagoon. The fishes that had been held in the most acidic water demonstrated risky behavior: instead of staying close to a protective coral, they wandered farther away and did so more often than the fishes that had been held in untreated seawater. After a research diver scared them back into the coral, those that had been held in the higher CO_2 levels came back out quicker than the other fishes did. And sure enough, the bold ones exposed to the seawater for 2100 were nine times more likely to be eaten by a predator. Fishes exposed to the seawater for 2050 were not quite as bold but still wandered and were five times more likely to die.

Researchers like to use reef fishes for experiments because their behaviors are consistent and easy to observe. But, to date, more than 80 experiments on other sea creatures have shown disturbing behaviors as well. Scientists at the Monterey Bay Aquarium Research Institute raised hermit crabs in highly acidic conditions. The crabs did not show the significant increase in boldness that damselfishes did, but they took much longer than normal to reemerge from their shells when they were attacked by a simulated predator (a toy octopus).

Investigators in Chile worked with the Chilean abalone, a mollusk that adheres to rocks along wave-swept shores. Typically when rough waves dislodge the abalones from their perches, they quickly reattach themselves so they do not drift around, making them an easy catch for predators. When CO_2 levels were raised by about 50 percent, some abalones took less time than usual to right themselves. Some held in more acidic water took wrong turns while trying to avoid crab predators lurking nearby, and some actually turned *toward* the crabs' claws instead of away from them.

Clearly, ocean acidification is meddling with sea creatures' minds. But how? A few researchers wonder if the cues themselves—the smells and sounds—are altered by the changing pH. But experiments show that fish can readily identify chemical cues in high-CO_2 water. Other scientists hypothesize that the altered behavior could be a stress response in fish that are trying to regulate changing acidity in their body, but that requires further investigation.

On a different hunch, Philip L. Munday of James Cook University in Australia and I decided to collaborate with Göran E. Nilsson of the University of Oslo. Nilsson suspected that acidification interferes with a neurotransmitter receptor called $GABA_A$, which modulates signals in the brains and nervous systems of many animals, including humans. Among other tasks, $GABA_A$ inhibits signals by conducting chlorine and bicarbonate across nerve cell membranes. When fish are exposed to elevated CO_2 levels, they excrete chlorine from their body to accumulate more bicarbonate—an attempt to minimize pH change inside their body. This shift in chemistry, however, causes $GABA_A$ receptors to become excited, impairing signals. When fish exposed to high CO_2 are later placed in water with gabazine, a chemical that reduces the excitation, normal behavior resumes after only 30 minutes. Yet $GABA_A$ sensitivity may differ among species, so it is not clear if this is the primary cause for behavioral changes.

CAN FISH ADAPT?

THE MAIN QUESTION I receive when speaking about ocean acidification is, What are the chances that marine life can adapt? Nature has an astounding capacity to heal itself. Predicting how an organism might adapt is difficult, and predicting how well complex ecosystems can adapt is nearly impossible.

Experiments do indicate some common trends. For example, smell was altered for adult sharks as well as juvenile clown fishes. Recent scientific studies, however, have also identified fish species and life stages that appear to be more resilient to the behavioral abnormalities we observed.

We have to ask, however, if the rate of acidification in experiments is a complicating factor. Most studies have bred or habituated fish to elevated CO_2 conditions over a few days or months—an extremely short time frame. The animals are not given a realistic opportunity to acclimate or adapt. We will have to investigate fish in the wild as the ocean gradually becomes more acidic.

To gain insight, scientists have turned to reefs near volcanic gas seeps, where CO_2 comes up through the reef floor at spots, naturally acidifying the water there to levels anticipated by 2100. When we visited volcanic reefs in Papua New Guinea, we found that juvenile damselfishes at a seep site were attracted to a predator odor, did not distinguish between predator and nonpredator odors, and exhibited bolder behavior—the same oddities shown by our lab fishes. At nonseep reefs, the same damselfish species did detect and avoid predators and was less bold.

We also do not know if the behaviors might be passed on to future generations. Researchers are just starting to investigate. In one study, offspring of coral-reef fishes raised under high-CO_2 conditions showed no advantage in adapting to higher levels.

Ocean acidification is one of many stressors. Overfishing, increased water temperature, greater pollution, the removal of top predators such as sharks, and habitat destruction all hurt the sea. Although local issues such as shark finning can be stopped by authorities, broader insults such as increased temperature and acidification could be the straws that break the backs of many species. As we examine how stressors physically affect ocean dwellers, we should also investigate how they might affect cognitive abilities, which are just as important to survival. SA

Danielle L. Dixson is an associate professor of marine science and policy at the University of Delaware. She studies how climate change and habitat degradation affect the behavior of marine organisms.

MORE TO EXPLORE

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A NEW REALITY

Climate change is dramatically altering life at the top of the world

Text by Mark Fischetti, Maps by Katie Peek

On Banks Island in Canada's Northwest Territories, more than 4,000 slow-motion landslides are creeping downhill as thawing permafrost slumps and crumbles. In Siberia, warming earth is allowing underground methane seeps to breach the surface and explode, leaving craters up to 40 meters wide.

Across the Arctic, striking change is the new normal, as is incursion by countries and businesses. Construction, oil and natural gas extraction, shipping and tourism are all on the rise. Climate and human activity are leaving a mark on nature and on the four million people who live in the region.

As interactions widen, science will be important for informing agreements and policies, especially concerning disaster preparedness, environmental protection, economic opportunity, food security, human health and community resilience. Indigenous peoples may be among the most valuable experts. For years they have closely tracked shifting temperatures and receding ice cover, trekked mountains and forests, followed caribou herds, fished seas and maintained biodiversity. Their communities and cultures are also the ones most affected by coming development.

Some indigenous leaders say the Arctic should be governed by cooperative organizations and rules that transcend political boundaries. For example, land and marine spatial planning across large expanses could lay out rights for people, environmental protection and means for constructive dialogue. Ultimately, they say, sustainable use of the future Arctic depends on a healthy environment and a healthy community. SA

Mark Fischetti is a senior editor at *Scientific American*. He covers all aspects of sustainability.

Katie Peek, formerly the information graphics editor at *Popular Science*, is a science journalist and data-visualization designer.

DAVID YARROW *Getty Images*

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ARCTIC FULMAR flying over calving glacier, Northern Spitsbergen, Svalbard, Norway.

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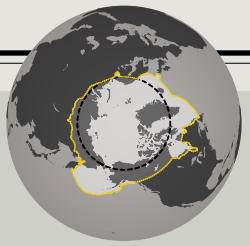
LAND OF CHANGE

Scientists are running out of words to convey how dramatically Arctic landscapes and seascapes are changing. Physical factors such as rising air and sea temperatures, along with disappearing snow and sea ice, are compounding the effects. As a result, living things from algae to trees to caribou are flourishing, floundering or moving; virtually every part of the food web has to adjust. Thawing permafrost could impact the region and the planet the most, releasing enough greenhouses gases to double the global warming that has already occurred.



Top of the World

The "Arctic" can be defined in different ways. The maps here follow the international Arctic Council's outline.

Physical Changes

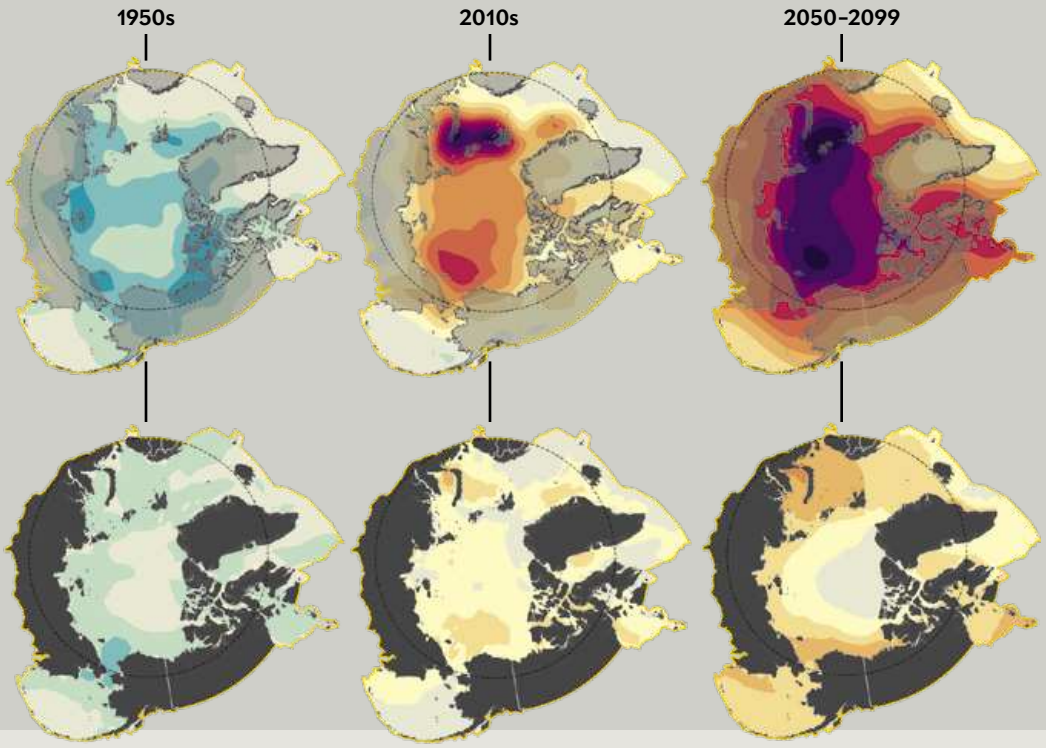
Air, sea and land are transforming rapidly. Each characteristic is mapped across the longest time interval for which comprehensive data exist.

Hotter Air

Average winter air temperatures at the surface in the 2010s have been much warmer than in the 1950s. The second half of this century will be hotter still, according to midrange projections.

Warmer Ocean

Summer sea-surface temperatures have risen considerably and are predicted to continue upward.



Nature Responds

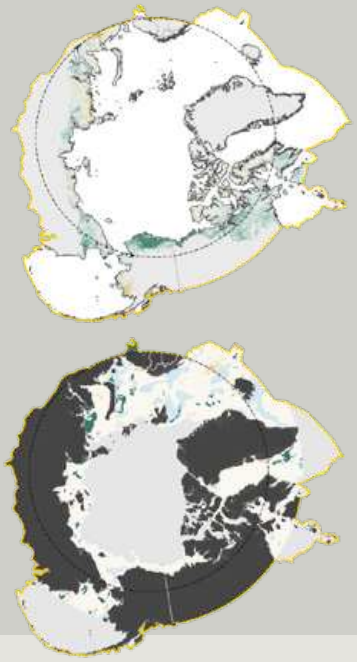
Life in all forms is adjusting to changing conditions.

Tundra Is Greening

Satellite imagery shows how much greener or browner land areas appeared in 2017 versus 1982, based on vegetation cover.

Algae Are Growing

Warmer and more ice-free seas allow phytoplankton to thrive. Their extent, seen as green by satellites, in summer 2017 was greater than in summer 2003.



North American beaver

The Beaver Effect

As trees migrate north, beavers follow. They fell the trees and build dams, causing local flooding that thaws permafrost, which releases carbon dioxide and methane. The gases enhance warming, and trees grow farther northward. More beavers arrive, more dams go up, more flooding thaws more ground and warming continues to increase.

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Less Sea Ice

Sea ice shrinks to a minimum every September. Much more disappears annually now. The median year for 1850–1859 was 1855 (based on map, sailing and explorer records); the median year for the most recent decade was 2010.

Ice extent in September

Sea ice present

Less Snow

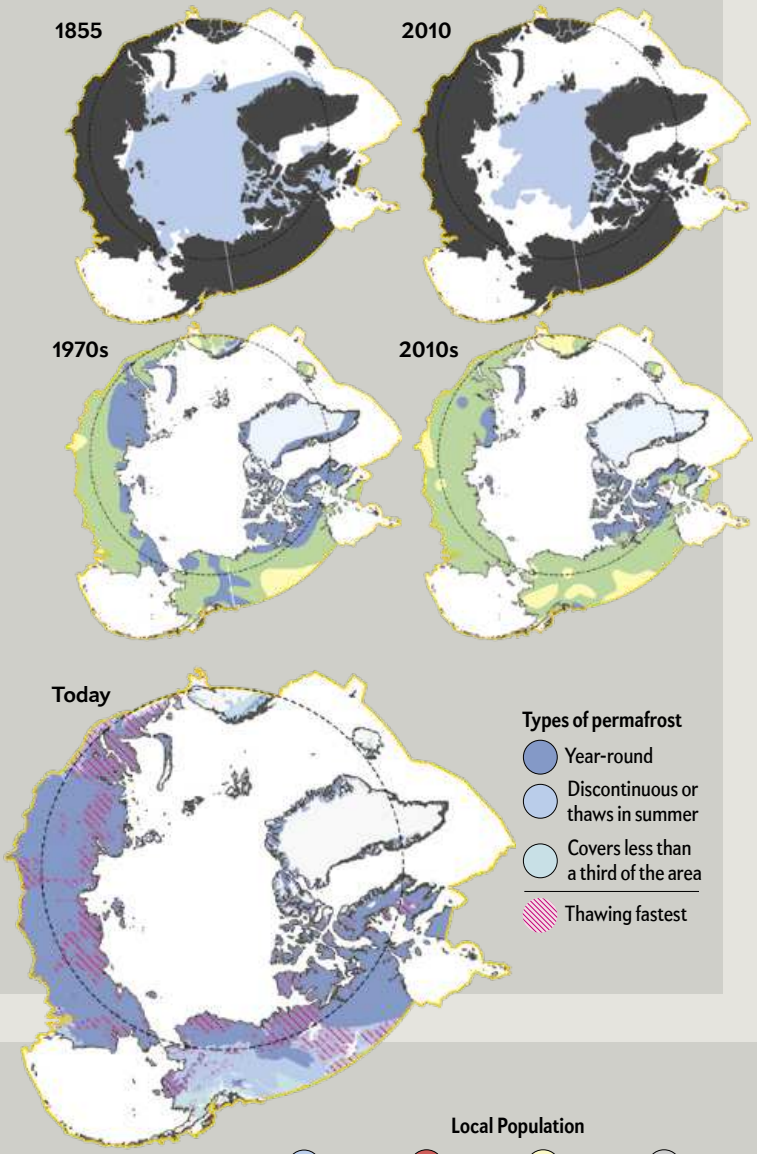
The number of weeks with snow cover has diminished significantly from the winter of 1972–1973 (median for 1970s) to 2008–2009 (median for past 11 years).

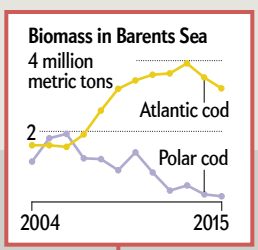
Weeks with snow cover

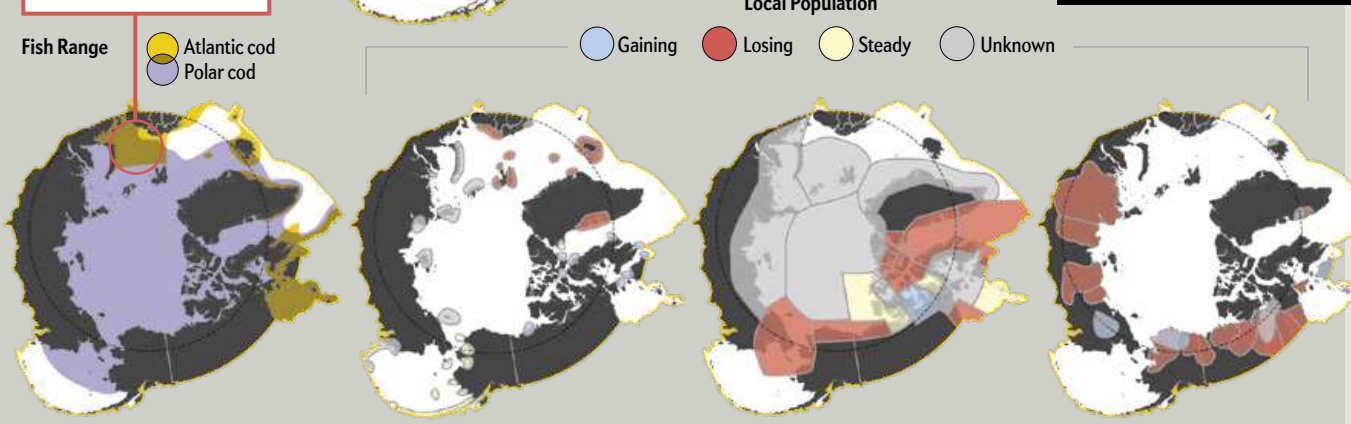
20 — 50+

Softer Permafrost

Ground that used to be frozen for most or all of the year—permafrost—is thawing, slowly in some places, quickly in others.







Fish Are Migrating

Polar cod rely on sea ice to spawn. As oceans warm, their numbers are falling, whereas Atlantic cod are moving in from the south.

Birds Are Shifting

Thick-billed murres nest in vast coastal colonies and are important prey for humans and animals. Their numbers are waxing in some places, waning in others.

Polar Bears Are Dying

Struggling polar bears are the icon for a melting Arctic. Their demise is widespread.

Caribou Are Wavering

Of the 23 tracked herds of caribou (reindeer), 16 are losing population, five are gaining and two are holding steady.

MORGAN TRIMBLE *Getty Images (beaver)*; ADRIAN WOJCIK *Getty Images (Longyearbyen)*; SOURCES: NOAA'S EARTH SYSTEM RESEARCH LABORATORY (*air and sea-surface temperatures*); U.S. NATIONAL SNOW AND ICE DATA CENTER (*sea ice*); NOAA'S NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION (*snow cover*); MERRITT R. TURETSKY *University of Guelph* (*permafrost*); UMA S. BHATT *University of Alaska Fairbanks* (*tundra greening*); KAREN E. FREY *Clark University* (*primary productivity*); FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (*cod habitats*); *STATE OF THE ARCTIC MARINE BIODIVERSITY REPORT*, CHAPTER 3.4: "MARINE FISHES." CONSERVATION OF ARCTIC FLORA AND FAUNA (CAFF), 2017 (*cod abundances*); BIRDLIFE INTERNATIONAL, 2018 (*murre breeding locations*); *ARCTIC BIODIVERSITY ASSESSMENT 2013*. CAFF, ARCTIC COUNCIL, 2013 (*murre trends; polar bear trends; reindeer and caribou trends*))

Hotspot Svalbard

Norway's Svalbard archipelago is changing dramatically. Winters are seven degrees Celsius warmer and two months shorter than in 1971. Rain, once uncommon, routinely floods the thawing, slumping soil, as buildings sink into it. The rains can freeze lichens and mosses, however, forcing reindeer to eat the less nutritious kelp that washes up along softening shores. Inland, the Global Seed Vault, once buried in frozen ground, is losing its natural coolant.

Town of Longyearbyen on Svalbard

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Can We Save the

Scientists are urgently transplanting, fertilizing and enhancing corals to help them adapt to warmer oceans, but rebuilding entire reefs will be daunting

By Rebecca Albright

ACROPORA CORAL in the Great Barrier Reef releases bundles of sperm and eggs. Corals along the reef's thousands of kilometers spawn once a year, during late summer.

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Corals?

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I'M STANDING ON A BEACH IN AUSTRALIA, TOES DIGGING INTO THE SAND, ZIPPING UP MY wet suit before I dive down to the Great Barrier Reef. As I stare out at the ocean, I'm excited by memories of my previous dive at this site a decade earlier. Growing up in Ohio, I had spent my childhood reading *A Day in the Life of a Marine Biologist* when I wasn't glued to the Discovery Channel. I got certified for scuba diving in one of Ohio's murky limestone quarries and made it to the Great Barrier Reef a year later. I'm remembering the anticipation squeezing my chest the day of that dive. My friend Emily, now an expert in marine algae, and I took bets on how long we could make our air last, which turned out to be about two magical hours. We were mesmerized by a forest of vibrant corals teaming with cuttlefish, giant purple clams and graceful sea turtles.

Now I am back, this time as a postdoctoral researcher at the Australian Institute of Marine Science. I wade in up to my chin, tip my head underwater and look through my mask. My heart drops. Gone are the cuttlefish. Gone are the giant clams. Gone are the turtles. The corals are drab. Most of the thriving life has been replaced by algae and sediment. Although I know senior scientists who shared gut-wrenching stories of how a particular reef had degraded over their long careers, I feel I am too young—barely 10 years in—to see this alarming degree of change. Shouldn't I be having this experience at the end of my tenure, not the beginning? Or better yet, not at all?

My shocked realization happened in 2014, as the third global mass-bleaching event began. Corals, often mistaken for rocks, are made of living animal tissue that contains microscopic algae, which provide the organism with food and give it color. When rising ocean temperature stresses corals, they expel the algae, causing the tissue to bleach—turn white—and leaving it vulnerable to starvation and disease. The mass bleaching persisted for three years, ruining reefs and breaking hearts worldwide. Although coral reefs can be threatened by overfishing, pollution and ocean acidification, the rapid and widespread destruction from warming is the greatest concern today.

DIVERS secure new coral fragments raised onshore at Florida's Mote Marine Laboratory back onto a reef so they will grow and fill it in, a strategy similar to reforestation on land.

The first major global bleaching events hit in 1998 and 2010, each time triggered by warming seas worsened by El Niño conditions. The 2014–2017 event was by far the longest and most extensive, harming more than 70 percent of the world's coral reefs. Two thirds of the Great Barrier Reef were reported as dead or severely bleached, and the devastating effects continue. Reefs are disappearing before our eyes. In the past 30 years we have lost around 50 percent of corals globally, and a recent report released by the United Nations's Intergovernmental Panel on Climate Change (IPCC) estimates we're at risk of losing more than 90 percent of coral reefs by 2050. We need solutions, and we need them fast.

Although reefs cover just 0.1 percent of the ocean floor, they support nearly 25 percent of all marine species, including fisheries that feed millions of people worldwide. They also provide natural breakwaters that protect coastal communities by reducing wave energy by up to 97 percent and wave height by up to 84 percent. And they generate vast tourism revenue. If we lose reefs, we jeopardize the livelihoods of 500 million people and more than $30 billion annually in goods and services. Even if you

IN BRIEF

Ocean warming is killing corals. Scientists are trying several approaches to help them cope, including transplanting lab-fertilized corals into the wild.

Researchers have found that stressing corals can turn on genes that lead to more resilient offspring, and enhancing certain algae can boost coral health.

These techniques could restore reefs on a regional scale, but a worldwide revival can occur only if humans slow global warming.

PRECEDING PAGES: GETTY IMAGES; THIS PAGE: JOE BERG *Way Down Video*

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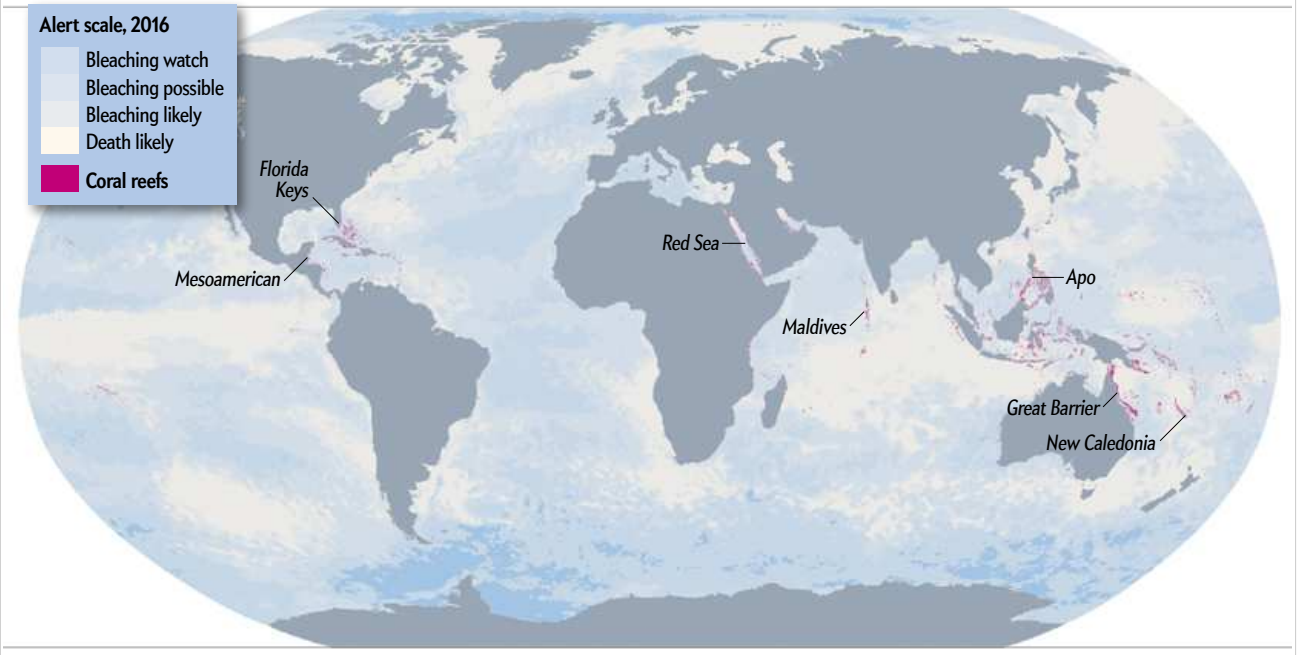
Worst Bleaching on Record

Relentlessly warm ocean water from 2014 to 2017 created the most extensive coral bleaching ever recorded. More than 70 percent of the earth's coral reefs were harmed. In 2016 alone (*map*), severe conditions spanned the globe (*white regions*). Hot water stresses corals, causing them to force algae out of their tissue, cutting off their food supply and leading to emaciation or death.



SOURCE: NOAA SATELLITE AND INFORMATION SERVICE

do not directly benefit from coral reefs, their destruction touches a chord in many people. As my colleague Luiz Rocha of the California Academy of Sciences puts it, "I may never live to see the *Mona Lisa,* but I still wouldn't want it to burn."

Driven by urgency, scientists are trying increasingly bold and creative ways to conserve and restore reef ecosystems. We are looking for techniques that are scalable and will not break the bank. Right now we are focusing on a handful of options that build on one another and can be integrated, including natural processes and human assistance. Together the steps might give corals the chance they need to make it through the coming decades, after which, it is hoped, the world will have drastically reduced its emissions, so warming will slow down.

I'm frequently asked: Will coral reefs survive? I think the answer is that they are resilient and might be able to cope, but they need breathing room—now.

NURSING CORALS BACK TO HEALTH

IF YOU WERE TO DIVE some seven kilometers off the coast of Florida, you might happen on one of several underwater forests of plastic trees with corals suspended from branches, like ornaments decorating a Christmas tree. Researchers are using such nurseries, as well as ones on land, to grow corals that can then be transplanted, or "outplanted," onto degraded reefs. Nurseries take advantage of the fact that all corals can reproduce sexually and asexually. Corals are clonal organisms—animals that are made up of hundreds to thousands of genetically identical polyps that are all clones of one another. They can reproduce sexually by creating eggs and sperm that fuse to create larvae and asexually when one polyp buds another.

When a coral is damaged by a storm, a piece of a colony might break off, tumble away, and eventually reattach to the bottom and continue to grow by cloning itself. Nursery practitioners can therefore deliberately fragment corals to create genetically identical clones. Today almost 90 species are successfully farmed around the world. Practitioners in the Caribbean and western Atlantic now grow and outplant tens of thousands of corals onto degraded reefs every year, often funded by private donors, grants or government restoration projects.

Scientists are looking to ramp up this restoration. About 14 years ago Dave Vaughan worked at Mote Coral Restoration. The techniques the researchers relied on then produced 600 corals in six years. The price tag on a single coral was about $1,000. But he discovered that because of a natural healing response, corals that are broken into tiny, eraser-size "micro fragments" can grow 25 to 50 times more quickly than corals in the wild. If pieces with the same genetic makeup (from the same parent) are placed a few centimeters apart, they will reconnect into a larger colony.

Now Erinn Muller, science director of Mote, says that the team can grow those 600 corals in an afternoon and has succeeded with all the half a dozen species it has tried; they are operating at less than $100 per coral, with some species costing only $25 per coral. By integrating citizen scientists and volunteers, Mote is convinced it can drop well below that number. The team can grow football-size corals that would have taken years to grow in the wild. Mote intends to produce and outplant up to 20,000 cor-

Map by Mapping Specialists

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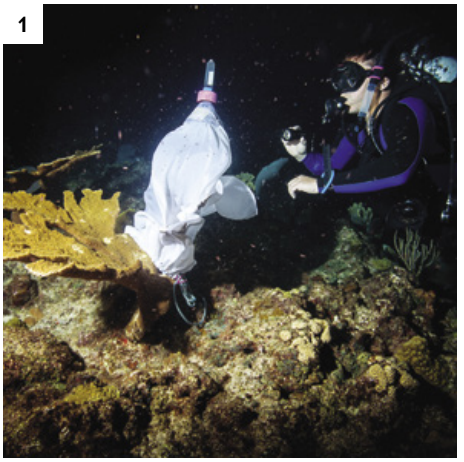
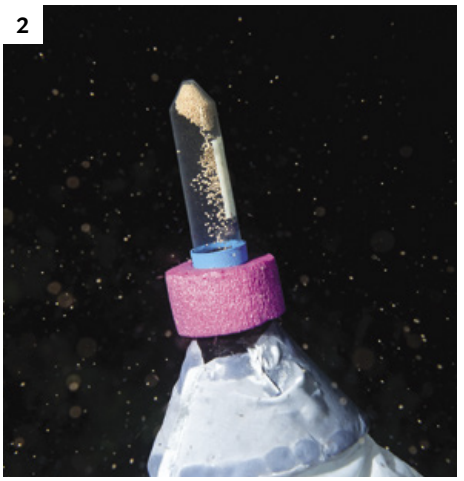
als each year and grow this effort in years to come. Although the U.S. National Marine Fisheries Service says recovering the endangered Caribbean staghorn and elkhorn corals will require a minimum of $255 million and 400 years, Vaughan, who now works at Plant a Million Corals in Florida, hopes to remove them from the endangered species list in his lifetime.

We're now very good at growing corals and can, in many cases, successfully restore reefs to their historical range and function—at the local level. But a jump to the ecosystem level is massive. One of the toughest challenges is how to meaningfully scale restoration efforts to the big leagues. Most efforts cover less than a hectare, whereas reef degradation is occurring over hundreds to thousands of square kilometers. The price tag to replant the extensive Great Barrier Reef system, 2,300 kilometers in length, has been estimated at nearly $200 billion, using fragments at $5 apiece. But even that cost could be well worth it because the recovery would restore large fisheries that feed many people, create many jobs, and protect valuable coastlines and communities from storms.





ELKHORN CORAL'S sperm and eggs are collected underwater (*1*) in a tube (*2*). In the lab, researchers combine the gametes with those from other corals to make new varieties, which increases genetic diversity, improving resilience to ocean stresses.

CORAL SEX

ALONG WITH GROWING corals asexually in nurseries, scientists are having increasing success in helping corals reproduce sexually, which can broaden genetic variation. As populations decline, genetic diversity is lost, which lessens corals' ability to resist warming water. Many Caribbean reefs, for example, are dominated by a single clone, and both science and history teach us that relying on low genetic variation, particularly in times of environmental change, can lead to disaster. In the 1800s, for example, a single clone of the Irish lumper potato fed Ireland's growing population until a rot wiped it out, devastating the island's people and economy. A more diverse crop would have fared much better. As in potatoes and people, genetic diversity can make corals less susceptible to environmental stress.

Sexual reproduction is nature's way of building diversity. Corals are fixed to the ocean floor, so they cannot move around in search of a mate. To reproduce sexually, most corals release eggs and sperm into the water column where, fingers crossed, fertilization happens. In degraded areas, where corals are few and far between, this becomes increasingly unlikely.

At the California Academy of Sciences, we are partnering with The Nature Conservancy and Secore International, a coral conservation organization, to help shepherd corals through this tricky process. We now have a good idea of when different coral species spawn. On predicted nights of spawning—after sunset, near a full moon in late summer (corals are surprisingly romantic)—coral colonies release eggs and sperm. We descend into the water with nets to harvest them and transfer these gametes to the laboratory, where we fertilize them in buckets of seawater. The resulting larvae are generally the size of sesame seeds and are vulnerable to being eaten in the wild until they settle and start to grow, so we raise them until they are big and healthy enough to be outplanted onto the reef. The goal is not to replant entire reefs but to maximize genetic variation and to rebuild enough of the population so the reef can recover naturally and be more resilient to the environment.

Many reefs have low genetic diversity, preventing them from churning out coral babies. By combining asexual and sexual restoration techniques, we may be able to restore one reef to the point where it can rebuild healthy reefs nearby. The aim is to create something that has a life beyond itself.

In the wild, only about one in a million coral babies survive. We are doing everything we can to help them through the vulnerable early stages. We can now achieve almost 100 percent success in fertilizing corals in the lab and settling the larvae onto tiles that can be outplanted, increasing the number of sexually compatible individuals that can improve future reproduction without our help. At a spawning event in Curaçao in the Caribbean in 2017, I helped a team collect five million eggs from 25 colonies within two short days. This is a new record for SECORE "and shows the scales we could work with," says the organization's founder Dirk Petersen.

In addition to helping corals reproduce in the wild, a handful of groups have started trying to spawn corals in public aquaria. No small feat, as it depends on our ability to mimic the suite of environmental cues that trigger reproduction, including lunar and seasonal cycles. Luckily, technological advances in aquaria-control systems are making it possible. At the California Academy of Sciences, I lead a team that has achieved two successful coral-spawning events—an accomplishment achieved in only one other location worldwide, the Horniman Museum in London. Our goal is to use this system to better understand the fundamental biology underlying coral reproduction and develop and validate methods that will help scale restoration efforts in the wild.

One of the biggest hurdles is keeping baby corals alive once we place them back in the sea. After all, degrading conditions are the main cause of coral decline in the first place, so until we tackle

PAUL SELVAGGIO *Secore International*

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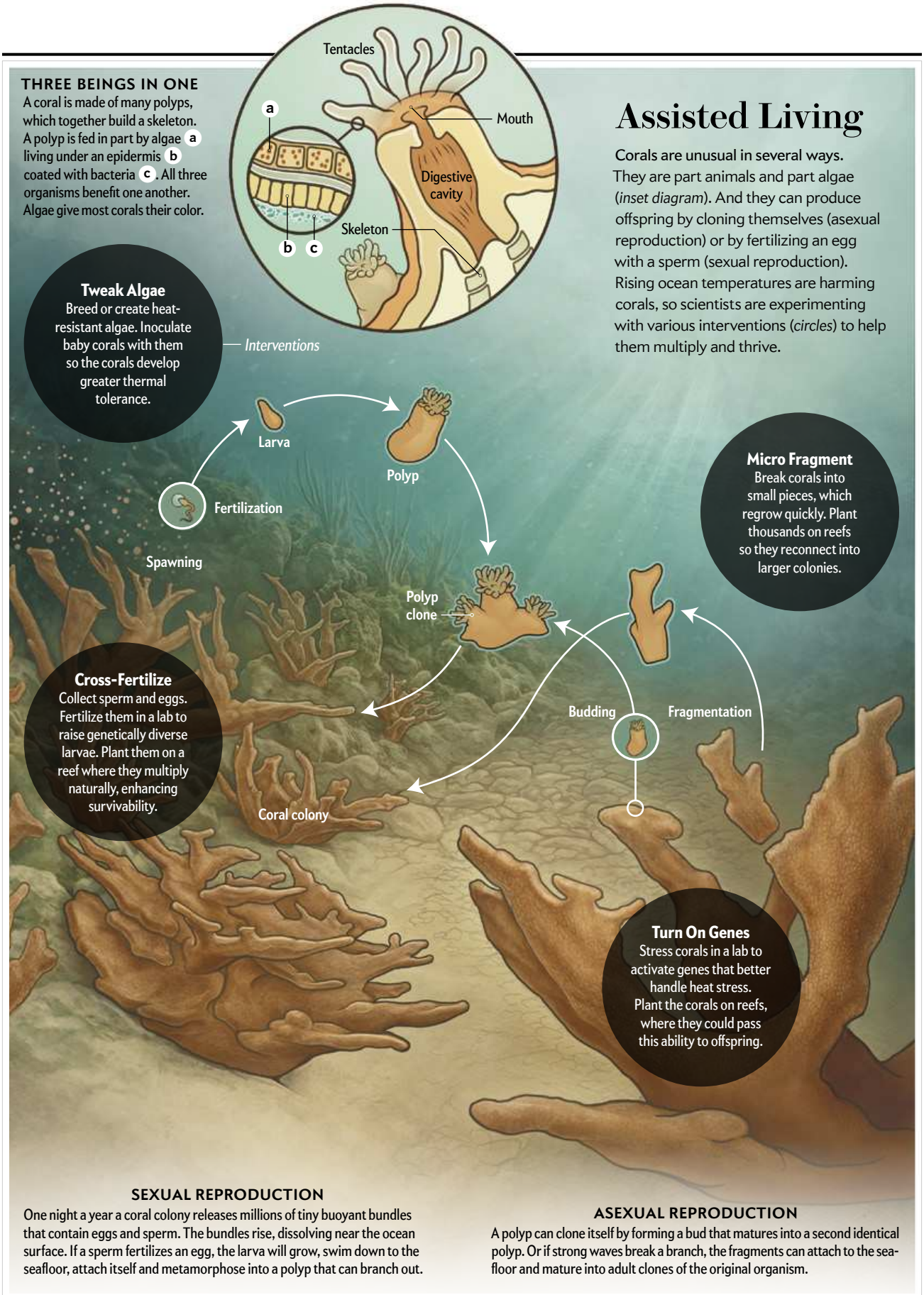
Assisted Living

Corals are unusual in several ways. They are part animals and part algae (*inset diagram*). And they can produce offspring by cloning themselves (asexual reproduction) or by fertilizing an egg with a sperm (sexual reproduction). Rising ocean temperatures are harming corals, so scientists are experimenting with various interventions (*circles*) to help them multiply and thrive.


THREE BEINGS IN ONE
A coral is made of many polyps, which together build a skeleton. A polyp is fed in part by algae a living under an epidermis b coated with bacteria c. All three organisms benefit one another. Algae give most corals their color.
Tentacles
Mouth
Digestive cavity
Skeleton
a
b
c
Interventions
Tweak Algae
Breed or create heat-resistant algae. Inoculate baby corals with them so the corals develop greater thermal tolerance.
Larva
Polyp
Fertilization
Spawning
Micro Fragment
Break corals into small pieces, which regrow quickly. Plant thousands on reefs so they reconnect into larger colonies.
Polyp clone
Cross-Fertilize
Collect sperm and eggs. Fertilize them in a lab to raise genetically diverse larvae. Plant them on a reef where they multiply naturally, enhancing survivability.
Budding
Fragmentation
Coral colony
Turn On Genes
Stress corals in a lab to activate genes that better handle heat stress. Plant the corals on reefs, where they could pass this ability to offspring.

SEXUAL REPRODUCTION

One night a year a coral colony releases millions of tiny buoyant bundles that contain eggs and sperm. The bundles rise, dissolving near the ocean surface. If a sperm fertilizes an egg, the larva will grow, swim down to the seafloor, attach itself and metamorphose into a polyp that can branch out.

ASEXUAL REPRODUCTION

A polyp can clone itself by forming a bud that matures into a second identical polyp. Or if strong waves break a branch, the fragments can attach to the seafloor and mature into adult clones of the original organism.

Illustration by Rebecca Konte

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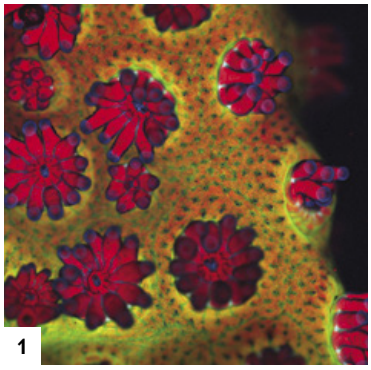
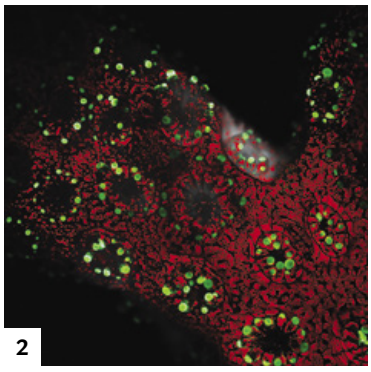
climate change, pollution and overfishing—via policy, awareness and global changes to the way we live—we are basically using a Band-Aid approach to buy reefs more time to try to survive. Along the way, we may be lucky enough to create genotypes through sexual reproduction that we could mass-produce with asexual techniques. We could then outplant them so Mother Nature could select which species might thrive.

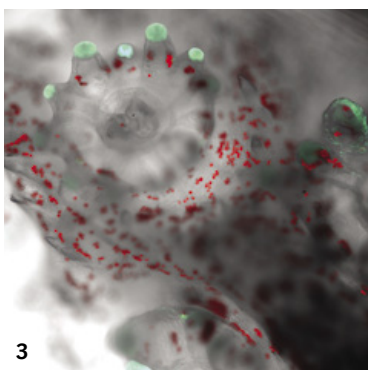
SUPERCORALS

WE CAN'T DEPEND ON good fortune for that scenario to happen. And because the ocean environment is changing too rapidly for many corals to adapt naturally, scientists are exploring other ways to accelerate the pace of adaptation. One approach is human-assisted evolution—enhancing traits that boost the capacity of corals, among other reef organisms, to tolerate stress and recover after bleaching events. Human-assisted evolution already surrounds our everyday lives. Most of the food we buy has been selectively bred or modified in some way (think "disease-resistant tomatoes"). Our pets have been selectively bred for certain aesthetics and personality traits. So why not breed or enhance corals to resist climate change?

Madeleine van Oppen of the Australian Institute of Marine Science and the Gates Coral Lab, directed by the late Ruth Gates, of the Hawaii Institute of Marine Biology are collaborating to enhance stress resistance. The Gates lab put corals on "environmental treadmills" to condition them to handle stress. Exposing certain corals in the lab to sublethal temperature stress may actually prompt them to turn on certain genes that help them better handle greater thermal stress in the long run. This process, known as epigenetic tuning, might be even more exciting if the trained corals are transplanted onto reefs, where they can transfer this ability to offspring, creating a generation of "supercorals." In theory, epigenetic tuning could enhance corals' ability to resist bleaching.







ALGAE (*red dots*) **feed a healthy** ***Pocillopora*** **coral (*1*). Warming seas drive them off (*2*) until the coral is bleached (3), starving it of sugars. (Green dots are proteins.) Scientists hope to devise heat-tolerant algae that would persist.**

We are only beginning to understand this process. Early lab tests are promising, but field trials have yet to be conducted. Once done, they will reveal whether transplanted corals confer enhanced abilities to subsequent generations, whether the approach can be scaled up and at what cost, and whether any inherent risks exist.

Van Oppen is exploring selective breeding. A certain amount of genetic diversity exists within each species, leaving some of them more or less resistant to bleaching or disease. As breeders do with pets to optimize desired traits, if we can identify resistant coral colonies and breed them to produce resistant offspring, we may be able to improve the temperature tolerance of an entire reef as subsequent generations pass down the useful genes.

Breeding corals is difficult because they can take up to a decade to fully mature. Adapting to environmental change is hard for the same reason. But microbes and algae that live in symbiosis with corals typically mature rapidly and can influence a coral's health tremendously. We are thus trying to manipulate these organisms via artificial selection in ways that boost coral health. In recent years scientists have realized just how much our microbiome (the bacterial communities inside our body) influences our health, for better, for worse. Probiotics are now available in everything from yogurt to kombucha tea and even chocolate, claiming to boost digestion, immune function and overall health.

Van Oppen is now developing strains of algae in the lab and inoculating baby corals with them to see whether they confer thermal tolerance. She and the Gates lab have also been attempting to see if epigenetic tuning, selective breeding and microbiome manipulations done on the same corals could possibly be even more effective in combination.

It is still early days for most of the techniques we are trying. But some evidence suggests that they could be combined for even greater success. This approach might look like the following: First, we would use sexual reproduction and assisted evolution to generate improved and new diversity among coral populations and to create individuals that have greater stress tolerance. Then we would mass-produce them in nurseries using asexual techniques and outplant them to reefs.

Could this happen soon? Not exactly. Some techniques, such as selective breeding, are immediately tractable, inexpensive and effective. But more work is needed to establish the viability and scalability of other techniques and to gauge the risks of unanticipated ecological consequences. It is possible, for example, that artificially enhanced organisms might possess novel traits that allow them to outcompete native populations rather than integrating with them, which would undermine the very goal of helping reefs thrive. It is also possible, however, that the risk of doing nothing could be far worse.

FROZEN FOR THE FUTURE

WHETHER WE BOOST CORALS using single or combined techniques, one other step is vital: preserving sperm, eggs, larvae and entire coral fragments in the equivalent of seed banks, which agronomists have used for decades to help raise crop yields, dis-

AMY EGGERS (1); AMY EGGERS, KATIE BAROTT AND MINDY MIZOBE (2, 3)

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RESEARCHER monitors transplanted corals in a bay surrounding the Hawaii Institute of Marine Biology to see how they are affected by acidic ocean water, another stressor imposed by climate change.

ease resistance and drought tolerance. The banks allow researchers to pull out biological bits and pieces as needed to further improve resilience and diversity.

Taking a page from the in vitro fertilization (IVF) handbook, Mary Hagedorn of the Smithsonian Conservation Biology Institute has established the first genome repository for endangered coral species. In IVF, sperm or eggs are cooled with liquid nitrogen to extremely low temperatures. The eggs can be thawed, fertilized in the lab and transferred to the uterus as embryos. Originally developed for humans, the cryopreservation concept has spread to help endangered species worldwide.

In 2004, some years after the first human baby generated from a cryopreserved egg was born, Hagedorn created the coral cryoconservation program. Her team has developed a freezing system for sperm that can be applied to a wide range of coral species. To date, the team has successfully banked 16 species from around the world (2 percent of the earth's estimated 800 species). Thawed sperm have fertilization rates comparable to fresh sperm, and the resulting embryos develop normally into healthy juveniles.

Hagedorn has distributed this germplasm, or living tissue, to cryobanks in various countries. Theoretically, it could remain frozen and alive for hundreds to thousands of years. The germ line cells could later be thawed and used in natural and captive breeding programs. For example, frozen sperm could fertilize eggs from places far beyond the sperm's natural range, introducing new genes into the coral gene pool. And of course, the banks can preserve species that may decline or disappear if reefs collapse.

Hagedorn hopes to cryopreserve eggs (in addition to sperm) and whole larvae before moving on to entire micro fragments. She is also developing techniques to cryopreserve fish testes to help conserve reef-fish biodiversity. Ultimately she envisions a future in which the germplasms of corals and other endangered reef organisms are deposited in highly secure facilities, making eggs, sperm and embryos available to broaden genetic diversity and rebuild reefs. "We have no idea what science will be able to do in 100 years," Hagedorn says.

Where do we go from here? Although some of these solutions may seem too unconventional by today's standards, we must invest in strategies for tomorrow. Many of these techniques have yet to be tested beyond the conceptual or lab stage, and questions remain about the scalability, costs and ecological consequences of manipulating reef systems. The consequences of doing nothing, however, threaten corals and the many species that rely on them.

What we know for sure is that there is no single fix to the problems plaguing coral reefs. Scientists are throwing everything they have at different options to buy reefs time. Although none of today's techniques is likely to salvage reefs at the global scale, many show promise on local or regional levels. The reefs of tomorrow may not resemble the reefs of today, but they can still provide important goods and services to ecosystems and to people. Climate change, pollution and overfishing are the larger challenges. We have to tackle them collectively to protect oceans overall and give coral reefs the breathing room they need to survive. SA

Rebecca Albright is a coral biologist and curator at the California Academy of Sciences. She focuses on how coral reef ecosystems cope with changing environmental conditions.

MORE TO EXPLORE

Global Warming and Recurrent Mass Bleaching of Corals. Terry P. Hughes et al. in *Nature*, Vol. 543, pages 373–377; March 16, 2017.
California Academy of Sciences' reef program: **www.calacademy.org/explore-science/hope-for-reefs**
Mote Marine Laboratory's micro fragment program: **https://mote.org/research/program/coral-reef-restoration**
Secore International's coral conservation program: **www.secore.org**

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ADAPT OR DIE:
Sitka spruce in British Columbia may need to borrow genes from trees in warmer climates.

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FORESTS ON THE MARCH

Trees can't walk to a better place as climate worsens. So scientists are relocating helpful genes instead

By Hillary Rosner

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IN A FIELD IN VANCOUVER, ACROSS THE ROAD FROM A ROW OF TIDY WHITE TOWNHOMES, roughly 500 bushy Sitka spruce trees climbed toward the sun. On a spring day in 2013 the trees, triangle-shaped with tightly packed, deep-green needles, were crammed shoulder to shoulder—or, in some cases, shoulder to waist. Although the spruces were all planted at the same time, seven years earlier, their height varied like primary schoolchildren assembled for a group photograph.

The smallest trees, around two feet tall, hailed from Kodiak Island, Alaska; the tallest, at nearly seven feet, originated in Oregon. Height was not the only visible difference. The spruces from Alaska produced buds a full three months earlier—an entire season—than those from Oregon. The Alaska trees also stayed green and healthy no matter how low the temperature dropped.

The spruces had been rooted in this field, at one end of the University of British Columbia's rambling campus, as an experiment to highlight how trees adapt to local environments. That trees match their habitats may sound obvious. But the details are important because of a looming threat: those habitats are changing as the planet warms—and trees can't exactly get up and walk to a new home. If a species cannot keep pace with a changing climate, it is doomed.

Because the trees themselves cannot relocate, scientists are exploring a novel solution: relocating the plants' DNA. That is why Sally N. Aitken planted the spruce garden. Aitken, director of the university's Center for Forest Conservation Genetics, believes saving the forests of British Columbia—and others around the world—may hinge on a practice called assisted gene flow. It could help species adapt to future conditions by moving organisms with particular traits from one part of their natural range to another. The tree from Oregon and the tree from Alaska just might have some genes that could help each other out. But without intervention, they would never meet.

Like an arboreal matchmaker, a forester could take seeds from spruces or lodgepole pines at a low elevation, say, and plant them farther upslope. As temperatures on the higher slopes warmed, the relocated trees would grow up and breed with their local counterparts, spreading their warm-adapted genes throughout the area and thus helping the forest adjust. Assisted gene flow could give species an evolutionary hand.

But you can't simply take a tree from Oregon, plant it 1,000 miles away in northern British Columbia and wait for the mercury to rise. The reasons that you can't come from the same local genetic adaptations that make the gene-flow idea attractive. Lodgepole pines, for instance, grow in different regions throughout much of the Canadian province. Their genes help some trees better tolerate heat or cold or drought or fend off local diseases or pests. If an Arctic cold front moves through Vancouver, hitting transplants from warmer regions, they will suffer. "We need to shift these things starting with baby steps," Aitken says. "The changes projected over the next few decades are really big, but we still have a lot of year-to-year and week-to-week and month-to-month variation that those trees have to survive."

Figuring out how to match today's seeds with tomorrow's climates is no easy task. But in British Columbia, where forestry accounts for a third of all exports and commercial forests make up nearly half of the total forest cover, it is vital. Provincial law requires that forests be replanted after logging, to bolster future timber supplies and healthy ecosystems. Roughly 250 million seedlings are planted annually. Just where those seeds should come from and how far they can or should be moved is a complicated—and pressing—question. Do it wrong, and you could be dooming the forests for decades to come.

The Sitka spruce experiment, which involved trees from 14 different locations ranging from central California up to Alaska, was Aitken's small proof of concept for a larger effort to avoid this type of fatal misstep. The research yielded 35 segments of DNA associated with cold tolerance and bud timing. Next Ait-

IN BRIEF

Forests adapt genetically to survive in local conditions, but climate is changing faster than trees can adjust.

To prevent forest death, scientists are moving trees with genes tied to water use and heat tolerance near other trees that need this DNA so they can breed.

Assisted gene flow, as the strategy is called, is being tested on trees from different climate zones in British Columbia.

PRECEDING PAGES: TJ WATT

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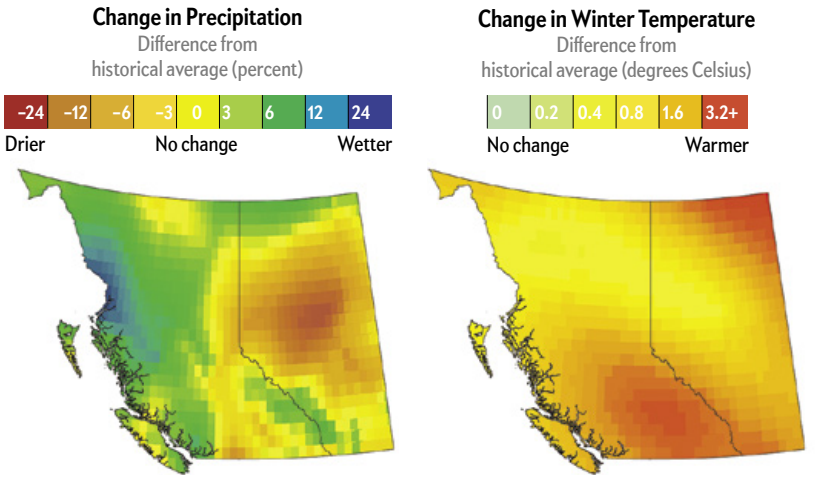
Weather Trends for Trees

Scientists compared the past with the present to figure out recent climate trends in British Columbia and Alberta and whether they depart from what trees experienced during the latter half of the 20th century. Researchers gathered direct observations from weather stations throughout the provinces between 1961 and 1990. The scientists compared this baseline with averages from a more recent period, 1997 through 2006. For the recent period, they noted whether the averages were wetter, drier or warmer or did not change from the earlier averages. They learned that the climate has become much wetter along the Pacific coast, which the researchers link to outbreaks of previously rare pine needle blight. At the same time, it has become drier in the interior, which may account for spruce and aspen deaths there. Winters have been warmer all over the provinces, allowing the tree-killing mountain pine beetle to spread to more forests. (Methods for this analysis were published in 2009 in *Agricultural and Forest Meteorology*.)



ken and her team sifted through more tree genomes to find genes responsible for proteins that are linked to other environmental traits. By examining these genes and comparing them among species (lodgepole pine and two varieties of spruce), they were able to show that closely related species adapted in similar ways using the same genes. Their hope is that beneficial versions of these genes—called alleles—would spread through populations that need the traits, in rough synchrony with the climate changes that make those genes useful.

The project, called AdapTree, as well as a more recent effort, CoAdapTree—which looks at three more species of conifer—could help pave the way for future assisted gene-flow projects around the world, work that could in turn help other species that are key ecosystem architects. Started in the fall of 2016, the project looks not just at climate adaptation but also at two tree diseases. "Insects and diseases are increasing their impact as the climate warms," Aitken says. The effort is co-led by a forest pathologist, Richard Hamelin, and is examining both tree responses to the diseases and the ways that the pathogens themselves vary genetically.

Aitken and Michael C. Whitlock, a population geneticist in the university's zoology department, coined the phrase "assisted gene flow" in a 2013 paper. Over the past decade scientists and conservationists have been arguing over a more grandiose idea, "assisted migration," which generally refers to moving species greater distances, outside their natural ranges. But assisted gene flow within a species' range is a more measured approach with genetic rigor at its heart. By the time AdapTree wrapped up, scientists had assembled DNA-sequence information for 12,000 lodgepole pine and spruce trees from more than 250 populations across British Columbia and Alberta.

CLIMATE ZONES

THOSE TREES are already feeling the effects of a changing climate. Back in the 1970s, British Columbia's government produced a climatic map of the province, organizing it into a series of biogeoclimate zones. That map has underpinned forest planning in western Canada for four decades, helping to govern which seeds can be planted where. Today, though, thanks to climate change, nearly a quarter of the map is obsolete. Some zones have moved, and others have dwindled dramatically. High-elevation zones and some interior plateaus have already lost around half their habitat—and could shrink by more than 80 percent by 2100. Seeds of trees that once would have thrived in a particular area might today be unable to even grow there. Zones may morph into ecosystems that are fundamentally different from what existed before, although exactly how much change is required before an ecosystem is "fundamentally different" is unclear and controversial.

Whether a particular population can adapt to change depends in part on how quickly the organism reproduces. Each new generation represents a chance to acquire useful traits. So a pine beetle, which reproduces quickly, has a much better chance of adapting than a tree, which is long-lived and slow to reproduce. A single bug may witness no change at all during its life span. A tree, though, has a front-row seat to global warming.

A stand of forest is most at risk during its first 20 years of life. Once the trees are established, they become far more resilient, "able to stick around for a while," says Brad St. Clair, a research geneticist at the U.S. Forest Service in Corvallis, Ore. But in the era of global warming, local conditions can change considerably over those two crucial decades.

"If you're going to move things to higher elevations so they'd be adapted to future climates," St. Clair says, "then they have to be adapted to cold-hardiness now." In other words, if you move warm-adapted trees now into a zone that is projected to warm in the future, those trees could be in short-term trouble because the zone is still cold today.

"We've got a moving target," Aitken admits. "Do we want to

Maps by Andreas Hamann

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best match trees with climate when they're seedlings? Or 10 years old? Or 30 years old?" One way to manage risk is to increase diversity—which might mean mixing local and nonlocal seeds. "You don't want to do the same thing on every hectare of ground. You can't plan around a single climate change scenario."

Assisted gene flow may be a good way to bulk up a forest's genetic diversity, sprinkling its gene pool with the ingredients that give trees a boost. As the environment shifts, some trees may suffer in the short term, but other trees will have genetic material that could help the forest weather tough times. "As those individuals that are more fit reproduce more," Aitken says, "we expect populations to start expanding again." The critical element, she says, is maintaining enough healthy trees to mate and survive while the process of adaptation unfolds.

SEEDS OF CHANGE: The AdapTree experiment gathers seeds from different habitats (*1*). Pine seedlings grown in the project's greenhouse (*2*) show variation in shape (*3*). Some needles are tested with a probe (*black rod*) to see whether they can resist freezing temperatures (*4*).

Aitken, an avid backpacker and backcountry skier who owns a cabin in the woods of central British Columbia, hopes her work will help set new, smarter forest policy. She believes that if we do not begin practicing assisted gene flow, tree populations may begin to fail at the far northern or southern edges of species' ranges. "Trees might persist a long time, but they might stop reproducing," she says. "They'd be evolutionarily toast." They would become, she adds, a "land of the living dead." What's worse, they would hog space and sunlight that seedlings desperately need. Closer to the middle of a range, things would be a bit less dramatic. But trees might still grow more slowly or have trouble surviving. "Does that mean the populations there are just going to die?" Aitken asks. "Probably not. There's a lot of variation within populations. The species aren't going to go extinct, but I imagine you'd have pretty unhealthy-looking forests in the meantime." The poor health would harm other plants and animals because trees anchor entire ecosystems, providing food and shelter, regulating water flow and preventing soil erosion.

Around the world, Aitken says, "there has been very little attention paid to the movement of individuals within existing species ranges." The ecological risks are lower than transplanting truly foreign trees because such foreigners are not already part of the ecosystem, even though they may possess some desirable traits.

There are still risks to a gene-flow approach. It could, for instance, add local gene variants that would actually harm a larger population's chance for survival. "There is a risk that you could be introducing unwanted alleles," says Andrew Weeks, a geneticist at the University of Melbourne. But the problem would likely correct itself, he adds. "That's the beauty of natural selection, which will weed out these variants. By increasing the gene pool, you are giving the population the best chance for the future."

With British Columbia's forests worth $10 billion a year—as well as providing vital services such as preventing floods and soil erosion—doing nothing may pose an even greater risk. British Columbia has already seen what global warming can do to forests. Since the mid-1990s beetle invasions and wildfires, both linked to warming temperatures, have destroyed millions of acres of forest and consumed hundreds of homes. "We've had lots of wake-up calls here in terms of climate change," says Gregory O'Neill, a research scientist at British Columbia's Ministry of Forests and Range. The insects and fires, O'Neill says, left people in the province "quite cognizant of climate change—and not that it's some abstract thing in the future, but it's already happening."

The losses jolted the provincial government into action. In 2009 British Columbia began revising its rules on moving seed. That same year O'Neill began an assisted migration trial for the province's forests, hoping to determine whether, where and how foresters might plant completely different species after harvesting. At 48 sites throughout Canada and the western U.S.—from Whitehorse to Sacramento—researchers planted 15 species of commercially important trees, moving them from their home range and, in some cases, relocating them thousands of miles away.

The extreme migration, O'Neill says, is merely a research tool, a way to provide a better overall picture of how the trees will fare. It is not intended as a guide for long-distance moves. Any actual changes in planting patterns will be incremental. "Some-

JACK WOODS *AdapTree project, University of British Columbia (1);*
CONNOR FITZPATRICK *AdapTree project, University of British Columbia (2)*

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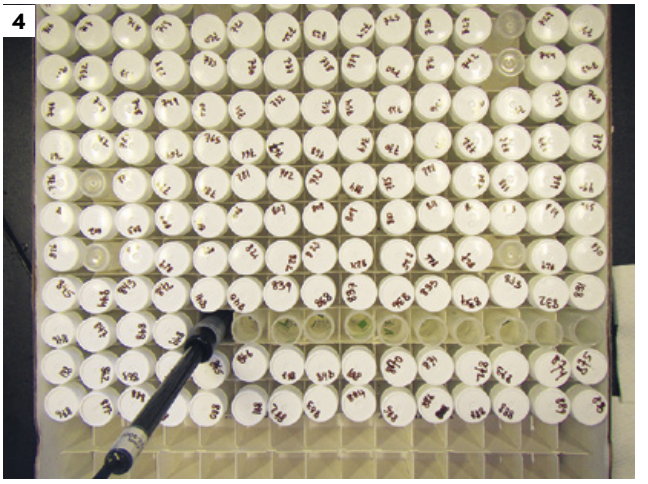
thing like 'Do not move your trees downhill' or 'Do not move your trees south,' " he says. There is a weather station at each site, and the study will show how the growth and survival of the seedlings relate to the local conditions. Then, O'Neill says, scientists will be able to predict how the trees will respond to climate change.

The genetic analysis of AdapTree offers a complementary way to predict how the trees will fare. Researchers on the sprawling project pored over DNA sequences from millions of locations in the genomes of interior spruce and lodgepole pine trees. They developed a quick screening method—similar to that used by the human genome screening business 23 And Me—that looks at roughly 50,000 short strings of genetic code, known as single nucleotide polymorphisms, or SNPs. With that done, they dug in, as Aitken put it, trying to zero in on the specific polymorphisms that match a tree to its home base.

3



4

The raw genetic data from AdapTree are dizzying. Printed on both sides of sheets of 8 ½ by 11 paper, Aitken notes, the stack would rise at least 90 miles. And that is only part of the information. Researchers are now looking at how the genes actually function—how their instructions are carried out—when the trees encounter stresses such as drought or high temperatures.

FORESTS OF THE FUTURE

A FEW DEGREES of latitude south, specialists in the U.S. Forest Service are beginning to weigh the pros and cons of assisted gene flow. "Where we're at is a lot of talk and discussion," St. Clair says. In the U.S., foresters historically did not focus on specific climate variations within zones where they collected and planted seeds. Moving seeds in a zone did not appear to involve enough temperature change to affect plant health.

Now foresters generally agree they need to get much better at moving seed. For as long as people have been planting trees, we have been relocating seed across rivers, villages, continents or oceans. "If you go back far enough, people used to move seed around all the time, and you'd often end up with failed plantations because people had no idea what they were doing," says Glenn Howe, a forest geneticist at Oregon State University. Partly as a result of those failures, over time the forestry community developed an aversion to risk. In the western U.S., seed zones, which guide how far seeds can be moved for planting, are narrow and conservative. "That's probably appropriate in a static climate," Howe says. "But with climate change, a very conservative approach could be a problem."

British Columbia is forging ahead. The province recently released new guidelines for reforestation, based in part on AdapTree's findings. Roughly 300 million seedlings were to be planted to regrow commercial forests in B.C. last year. As of April 2018, the guidelines were voluntary, to give companies time to shift their seed inventory, but within a couple of years they will be the rule.

Of course, broader challenges to assisted gene flow remain. For the moment, researchers will need to convince resource managers to trust in genomic data, something they cannot see for themselves in the field. Aitken says viewpoints are definitely shifting, particularly surrounding the idea of moving things around within a species' range. "I won't say there's no resistance, but there's not a lot of resistance," she says. Still, it is crucial that all those nucleotide polymorphisms and sequence data "translate into a forester's lexicon," Aitken says.

Because ultimately all those strands of DNA make up living, breathing trees—the ones we depend on to construct our built environments as well as our natural ones. To thrive in a changing world, some of those trees may need to branch out into new territory. And to do that, they are going to need our help. SA

Hillary Rosner is a freelance writer based in Colorado. She has written for *National Geographic*, the *New York Times* and *Wired*, among other publications.

JACK WOODS *AdapTree project, University of British Columbia (3);*
PIA SMETS *AdapTree project, University of British Columbia (4)*

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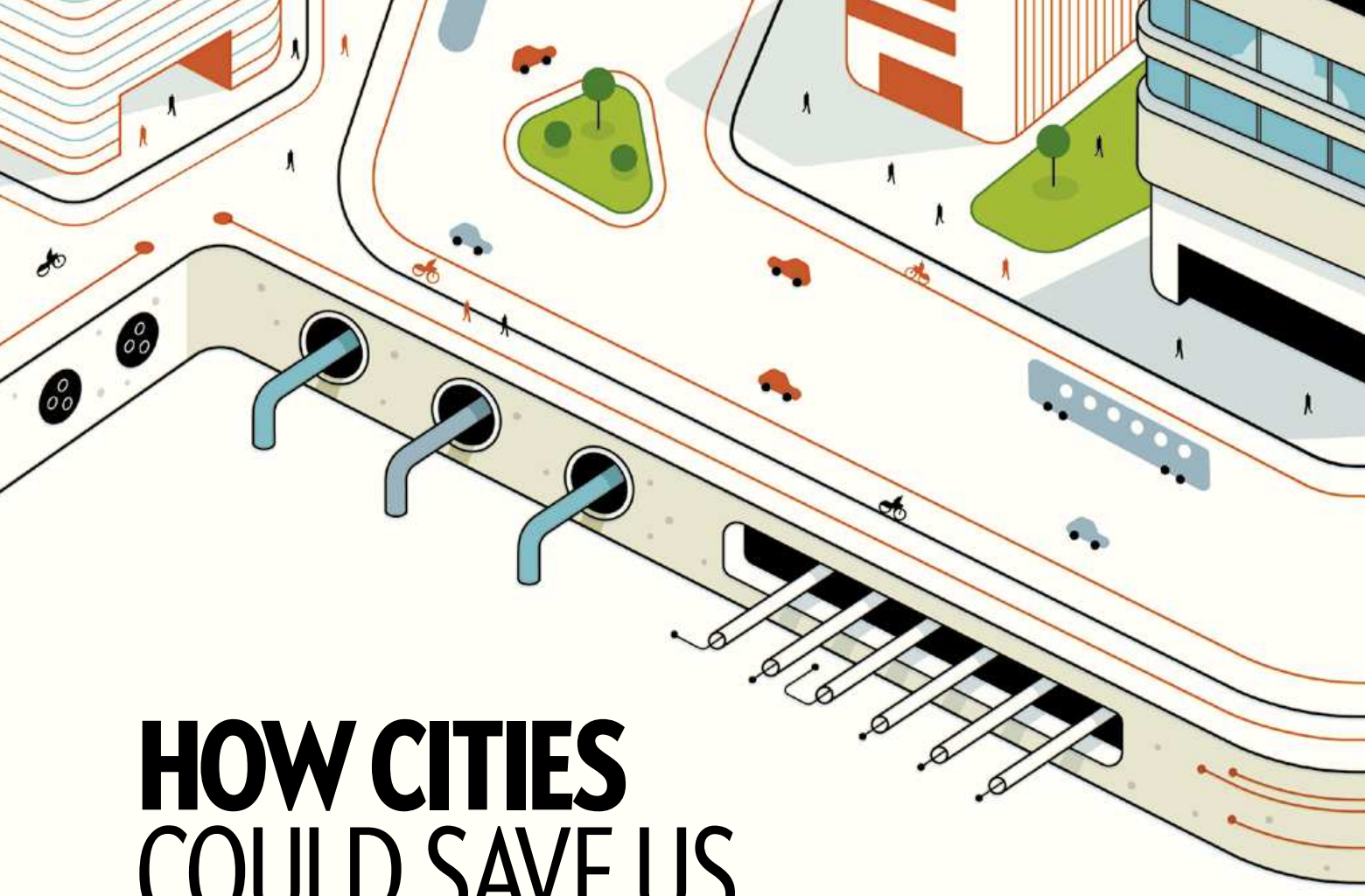

HOW CITIES COULD SAVE US

Urban areas can improve the planet as well as people's lives if we design them to be much more resourceful with energy, water, food and minerals

By William McDonough

CITIES ARE HOME TO MORE THAN HALF THE WORLD'S POPULATION, and they exert increasing stress on the earth. They produce up to 70 percent of global carbon dioxide emissions, use up vast quantities of water, degrade water quality and produce mountains of waste. As cities go, so goes the planet. And cities are growing—fast. By 2030, according to the latest United Nations estimates, five billion people will live in cities, nearly half of them conducting their lives in homes, schools, workplaces and parks that do not yet exist.

The challenges in making cities as sustainable as possible are enormous. But they are also inspiring because cities can play an outsized role in creating solutions for a more sustainable world. Cities are engines of innovation and entrepreneurial energy. As networks of city leaders are showing, municipalities are also powerful actors, pooling their strengths, setting environmental agendas and exercising global leadership. From megacities to towns, mayors and city councils, investors, economists and planners are responding to the urgent need to redesign the basic elements of

Illustration by Harry Campbell

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fast-growing cities from the ground up. How they reimagine the urban landscape and how they design growth will profoundly influence the future of all life on earth.

Many cities are taking important steps to reduce air and water pollution. They are being "less bad." Efficiency in itself, however, is insufficient to move us to a positive future. If cities can also be effective and do "more good," for example, by converting waste back into nutrients for food production, cities can propel us toward a future we want, not just reduce the impacts we do not want. More good, not just less bad.

A clear vision for reimagining the city and its relationship to its surrounding countryside can be found in replicating the operating system of the natural world. In essence, natural systems operate on the free energy of the sun, which interacts with the geochemistry of the earth to sustain productive, regenerative biological systems. Human systems, including cities, that operate by the same laws can approach the effectiveness of living systems.

These laws can be distilled into three key principles: equate waste with food; maximize use of solar income; and celebrate diversity.

Waste does not exist in nature, because each organism contributes to the health of the whole. A fruit tree's blossoms fall to the ground and decompose into food for other living things. Bacteria and fungi feed on the organic waste of both the tree and the animals that eat its fruit, depositing nutrients in the soil that the tree can take up and convert into growth. One organism's waste becomes food for another. Nutrients flow perpetually in regenerative, cradle-to-cradle cycles of birth, decay and rebirth. Waste equals food.

OUR CITIES are currently designed for linear flow. Biological nutrients (such as food and wood) and technical nutrients (such as metals and plastics) enter at one end and are used, then discarded. After waste is sifted for valuable recyclables such as metals, paper and certain plastics, it flows out the other end, headed for landfills or incinerators. The process is "take, make, waste." But just as we have redesigned certain consumer products to be disassembled, recycled or reused, we can design cities in a similar, circular fashion: take, make, retake, remake, restore.

In the circular city, wastes become resources. Consider sewage. In a linear city, wastewater-treatment plants process food residues and human waste—including the valuable minerals they contain, such as phosphate—and release the effluent into rivers as pollution. Farmers then buy more phosphate from Morocco or other distant lands to make new fertilizer to grow more food in soils that have lost those minerals. In the circular city, sewage-treatment plants become fertilizer factories. The carbon, phosphate and nitrogen flowing out of the facility are seen as potential assets for soil, not as liabilities for the nearest river. Circular cities mine the wastewater for phosphate and turn it into fertilizer for parks and vegetable gardens on city rooftops and for farms and forests surrounding the city. This process eliminates the need to buy more phosphate from faraway sources and transport it to the U.S. It also avoids the energy and carbon emissions involved in mining and transport. Ostara Nutrient Recovery Technologies in Vancouver is one of several companies pioneering the collection of the phosphate mineral struvite for fertilizer from sewage sludge.

Eliminating the concept of waste extends to all systems, so circular cities design incoming materials for "next use" instead of "end of life." For example, new technologies allow cell-phone circuit boards to be profitably processed in a clean facility, where all the rare earth minerals and precious metals are recovered for reuse in new electronic products.

A second key principle of nature, and what we might call positive cities, is that everything is powered by the sun—and sometimes, as in the Iceland city of Reykjavík, by geothermal power. Trees and plants manufacture food from sunlight—an elegant, effective system that uses the earth's only perpetual source of energy income. Buildings can tap into solar income by directly converting the sun to energy and by passively collecting the solar radiation for heat and natural lighting. Winds—thermal flows fueled by sunlight—can also be harnessed. Together solar, wind and geothermal energy can generate enough power cost-effectively to meet the needs of entire cities and regions, even nations. Cities such as San Francisco are already making significant progress toward meeting their commitments to run 100 percent on renewable energy in the next 10 years.

The third key principle—diversity—is found in all healthy ecosystems. Each organism has a unique response to its surroundings that works in concert with other organisms to sustain the system. Each organism fits in its place, and in each system the most fitting thrive.

Urban designers aiming for what fits attend carefully to local ecologies. They assess the geology, hydrology, vegetation and climate. They incorporate natural and cultural history. By combining this rich "essay of clues," designers discover appropriate patterns for the development of the landscape. By doing so, they create possibilities for positive growth that supports life.

Ultimately what we want is a city designed to allow people to live and work in the same neighborhood. If residents can decompose cell phones at a clean factory that fits within a city's ecosystem, there is no need to relegate the factory to special zones of bad behavior at the outskirts of town. A positive city eliminates the need for zoning driven by concern about unsafe or unhealthy activities. Factories can be in the middle of clean residential neighborhoods, providing jobs so people can live within walking or biking distance. That opportunity, in turn, greatly reduces the need for commuting and transportation—a huge waste of resources and of people's time. And if fresh, healthy food is grown on rooftops across the city, as Method Products' South Side Soapbox factory in Chicago is doing, not only can local organic waste be a resource for food-growing systems, but people working at the rooftop farms can live locally as well.

Imagine everything we make as a gesture that supports life, inspires delight and finds harmony with nature. Buildings operate like trees: they sequester carbon, make oxygen, distill water, provide habitat for thousands of species, and convert solar income into all the thermal and electrical energy they need—and sell excess power to the neighbors. Buildings with on-site wetlands and botanical gardens recover nutrients from wastewater and clean what remains for on-site kitchens and bathrooms. Fresh air, flowering plants and daylight are everywhere. Buildings and communities function as life-support systems.

With this vision in mind, we can imagine food and materials produced in the surrounding countryside, created with tools and technology made in the city. The city returns waste as a raw material that replenishes the system, putting the "re" back into resources. Everything moves in regenerative cycles, from city to country, country to city, in natural and cultural networks that circulate biological and technical nutrition—the hardware and software of the 21st century. The metabolism of a living, positive city allows human

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settlements and the natural world to flourish together. If we are to make our cities truly sustaining and beneficial for all, we need to take this as a literal, strategic truth that informs all our designs.

It is compelling to lay out principles for a utopian future. But can existing cities actually put them into practice today? Some recent industrial facilities are demonstrating how.

The renovation and expansion of the Ford Rouge Center in Dearborn, Mich., transformed the massive, historic car- and truck-manufacturing complex into a model of industrial sustainability. The master plan incorporated a 10-acre green roof—the heart of a system of wetland gardens, porous paving, hedgerows and bioswales. The project turned a 100-year-old industrial brownfield site into a thriving storm-water ecosystem that captures, cleanses and slowly releases water to the adjacent Rouge River in ways that support watershed health. Native killdeer returned to nest a week after construction was completed.

Another model is Sustainability Base, NASA's center for science and computing at its Ames Research Center in Moffett Field, Calif. The facility has the potential to provide all its heating, cooling and energy needs—and even an energy surplus—from solar and geothermal sources and a fuel cell with advanced energy-management controls. Wastewater is treated on-site.

The award-winning Park 20|20 development in Hoofddorp, the Netherlands, is another model. It is a diverse set of buildings and open spaces now being completed across 28 acres. People can access the park easily by air, rail, bus and bicycle. Green zones, plazas, public gardens and canal boardwalks provide a connection to the larger community. Each building's size, structure and orientation are optimized to capture the sun's energy and light. Buildings across the park integrate energy, water and waste-management systems, acting as a single organism.

CAN WE EXPAND these successes to entire cities? Inspiration comes from some intriguing places. One of them is Curitiba, Brazil.

Curitiba began transforming in the 1970s, under legendary architect and urban planner Jaime Lerner, who was mayor three different times from the 1970s to the 1990s. During his first term Lerner realized that the poor town of several hundred thousand inhabitants needed better public transportation. Because a subway or heavy rail system would cost far too much, he instead asked Volvo to make 270 Swedish articulated buses, done within the city, which gave residents jobs. The city hired locals to build aboveground, street-side bus shelters, or *tubos,* from which people could travel anywhere for a flat fare. Instead of riders paying with a token as they boarded a bus, a slow process, Lerner had them prepay when entering the *tubo* platform, so when the bus arrived, they could get on quickly, reducing loading time and making the entire system efficient.

As a result of Curitiba's rapid population growth, garbage was piling up in narrow alleyways where trucks could not retrieve it. Lerner created a program to instruct children how to separate trash, then sent them home to teach their families. In exchange for the sorted garbage, people were paid in bus tokens or fresh food; Lerner paid them in a currency for mobility. Suddenly, everyone was using mass transit. Today 85 percent of Curitiba citizens use the bus, and 90 percent recycle. Curitiba recycles 70 percent of its refuse—one of the highest rates in the world.

This innovative thinking went on and on. Instead of building a big central library downtown, the city created a network of 50 small "Lighthouses of Knowledge" throughout the neighborhoods so that every child was within walking distance of a library. Local builders, of course, constructed the brightly colored buildings. The libraries work with municipal schools and offer thousands of books and free Internet for citizens ages three to 80. These and other steps transformed the city to a live-work design.

Now imagine if Manhattan had this same kind of vision—with local food growing on the rooftops of hundreds of schools and hospitals, providing nutrition as well as local jobs. Kids could use their optical sensors known as eyeballs to sort trash, pull out the plastics, bring them to recycling centers so they do not end up in the ocean and then get paid in toys. Clean factories would reformulate the plastics into monomers that can be used again. Everything is powered by the sun, and materials flow in continuous cycles of biological and technical nutrition.

What we are after, for all people, is something I would call the "good life"—a life that is safe, dignified and creative. Positive cities are the places where that can happen. If they are designed and run on this principle, everything gets better. We have to insist on the rights of humanity and nature to coexist, to bring together the city and its surrounding countryside.

Cities are designed, but they are also organisms. As French anthropologist Claude Lévi-Strauss pointed out years ago, cities are "something lived and something dreamed." As makers of living places, we cannot help projecting ourselves onto the landscape. But as we dream of our ideal cities, as we conjure the human weft on the geologic warp of the land, we can begin to see more clearly the true character of the place we inhabit, its spirit. Then, as we shape the nature of our cities, we will be making places that celebrate both human creativity and a rich, harmonious relationship with the living earth. We will be forging a new geography of hope. SA

World population living in cities: **55%**

5 Billion

People living in cities by 2030

U.S. cities committed to 100% renewable energy: **150**

Residents who use the bus in Curitiba, Brazil: **85%**

SOURCES: *THE WORLD'S CITIES IN 2016: DATA BOOKLET*. UNITED NATIONS, 2016 (*population in cities now and in 2030*); SIERRA CLUB (*U.S. cities committed to renewable energy*); *LOW CARBON GREEN GROWTH ROADMAP FOR ASIA AND THE PACIFIC*. UNITED NATIONS ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC. U.N., 2012 (*bus use in Curitiba, Brazil*)

William McDonough is an architect who has pioneered design for sustainable development. He is founder of William McDonough + Partners and McDonough Innovation and co-founder of the Cradle to Cradle Products Innovation Institute.

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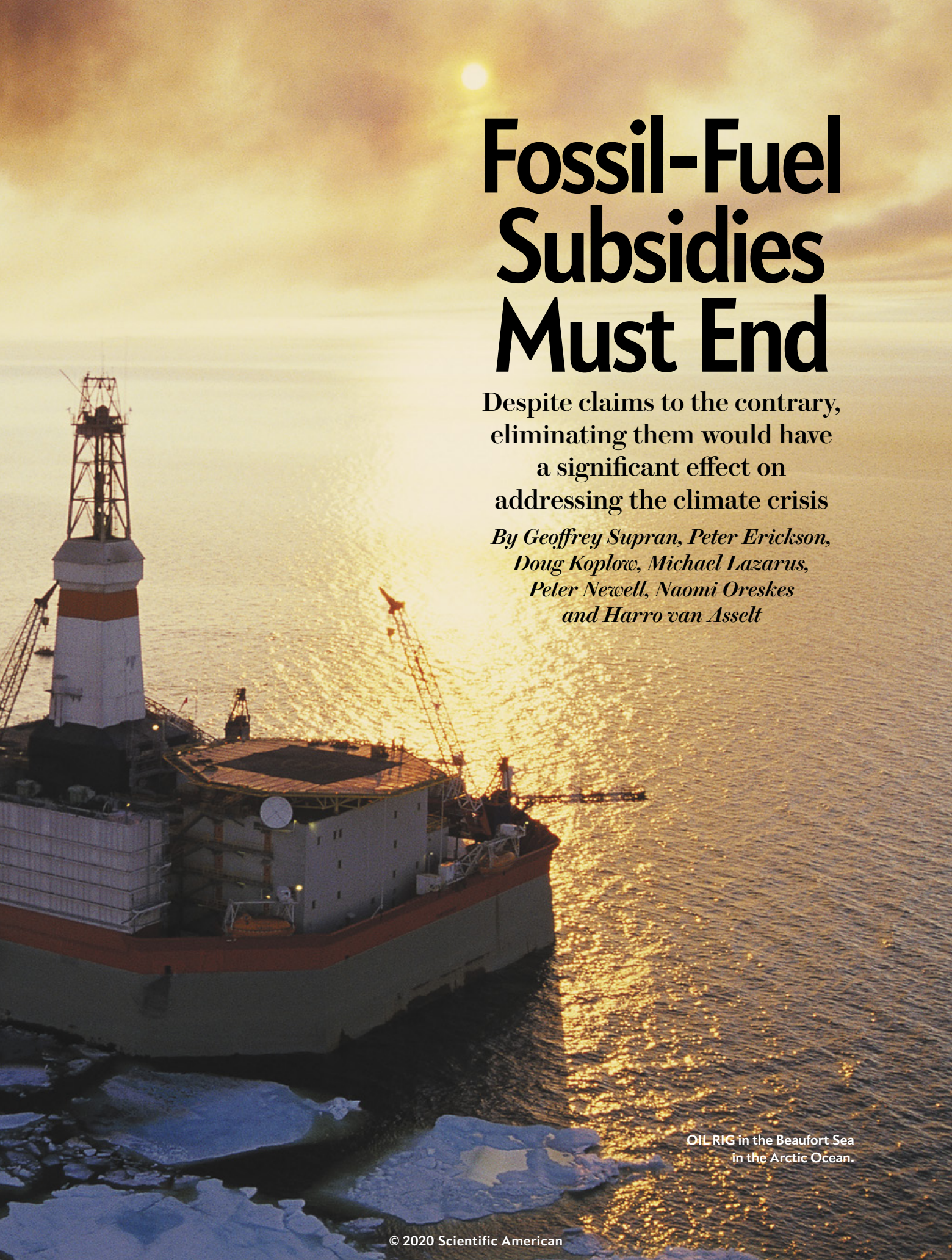
Fossil-Fuel Subsidies Must End

Despite claims to the contrary, eliminating them would have a significant effect on addressing the climate crisis

By Geoffrey Supran, Peter Erickson, Doug Koplow, Michael Lazarus, Peter Newell, Naomi Oreskes and Harro van Asselt



OIL RIG in the Beaufort Sea in the Arctic Ocean.

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WHEN IT COMES TO TACKLING THE CLIMATE CRISIS, ENDING $400 billion in annual subsidies to the fossil-fuel industry worldwide seems like a no-brainer. For the past decade world leaders have been resolving and reaffirming the need to phase them out. All the 2020 Democratic presidential candidates committed to eliminating fossil-fuel subsidies, and the vast majority of the American public supports doing so. International financial institutions such as the World Bank and International Monetary Fund have joined the chorus, pointing to the benefits of reform.

In 2018, however, a group of researchers questioned the magnitude of the climate benefits of subsidy reform, reporting that their simulations showed its effect would be "limited" and "small." Stories in the press began asking whether such subsidies are such a big deal after all.

We think this is wrong. In a paper in February in the journal *Nature,* we make the case that they do matter—a lot. In the 2018 study, emissions reductions from subsidy removal were calculated by the researchers to be 500 million to two billion metric tons of carbon dioxide a year by 2030. This figure is by no means "small." It amounts to roughly one quarter of the energy-related emissions reductions pledged by all the countries participating in the Paris Agreement (four billion to eight billion metric tons). Hundreds of millions of metric tons of CO_2 reductions is nothing to sneeze at, particularly when it can be achieved by a single policy approach that also brings strong fiscal, environmental and health benefits.

Moreover, previous work has more than likely underestimated the emissions reductions that would occur because commonly used techniques do not accurately capture the investment dynamics of fossil fuels. But these dynamics can greatly affect what oil and gas companies do.

AS THE DEPARTMENT OF ENERGY ITSELF CONCLUDED 40 YEARS AGO, FEDERAL SUBSIDIES HAVE HAD A "LARGE EFFECT" ON CAPITAL FORMATION AND OIL PRODUCTION IN THE U.S.

In our analysis of the issue, we take the example of one specific subsidy: a federal tax break that allows U.S. oil producers to immediately deduct from their taxes most of the costs of constructing and drilling new wells. Conventional models assume that such subsidies are uniformly distributed across all oil fields, whereas in reality, governments often preferentially target new—rather than existing—capital investments. The result is a lowering of producers' up-front cash-flow requirements, leading them to drill more new wells than they otherwise would. This process locks in and accelerates fossil-fuel production and, in turn, greenhouse gas emissions. We estimate that true emissions reductions from eliminating this tax-break subsidy could be more than an order of magnitude greater than was predicted using the conventional modeling approach.

And this tax break is just one subsidy. A separate, peer-reviewed analysis by some of us in 2017 demonstrated that without a dozen key subsidies, nearly half of U.S. future oil production could be unprofitable at $50-per-barrel oil prices—the level at which prices may hover in a low-carbon future.

In other countries, the forms of subsidies

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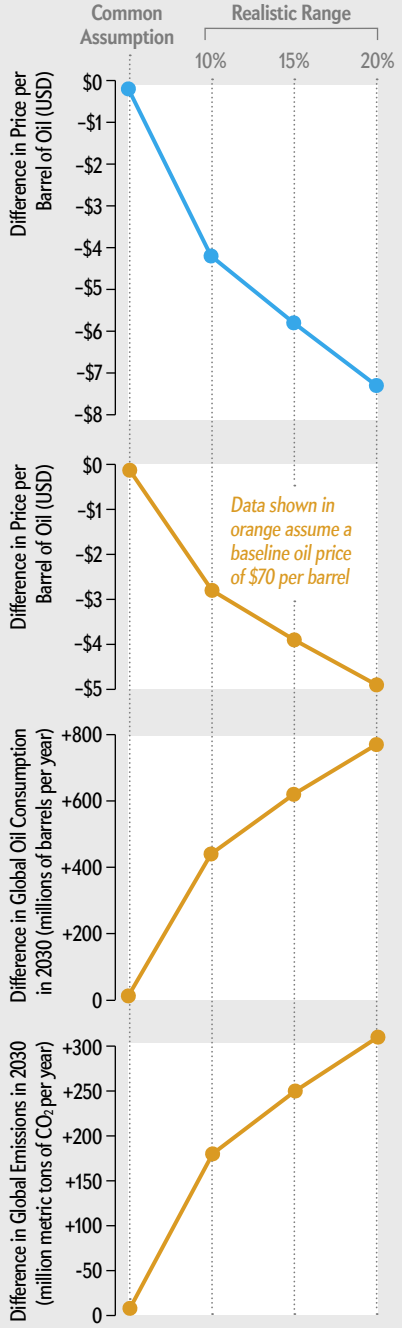
Impacts of Subsidies

When an oil company pays taxes can sometimes matter as much as the amount it pays. A tax break now can be used to drill more wells immediately, whereas one in the future cannot. In financial models, the value of delaying costs like taxes is called a discount rate; the higher it is, the more delaying costs matters. Our study evaluated how the value of the intangible drilling cost subsidy to oil producers in the U.S. depends on the discount rate and in turn how that can affect carbon dioxide emissions.



SOURCE: "WHY FOSSIL FUEL PRODUCER SUBSIDIES MATTER," BY PETER ERICKSON ET AL., IN *NATURE*, VOL. 578; FEBRUARY 5, 2020

can, of course, vary. But around the world, fossil-fuel production and consumption are supported in hundreds of ways. Indeed, the most troubling impact and legacy of fossil-fuel subsidies may be the political barriers—rather than financial ones—that fossil-fuel producers have erected against decarbonization efforts over a period of decades. Revenue boosts from subsidies can support not only more drilling but also product promotion, political activities and other efforts that reinforce the industry's incumbent status. Subsidies also have a symbolic effect, signaling that this industry and its activities are beneficial for society as a whole and that they therefore should be encouraged.

In another paper, published in a February issue of the *Proceedings of the National Academy of Sciences USA,* experts studying the social tipping points for climate stabilization concluded that "redirecting national subsidy programs to renewables ... or removing the subsidies for fossil-fuel technologies are the tipping interventions that are needed for the takeoff and diffusion of fossil-fuel-free energy systems."

Economic models provide useful guidance to policy makers. But as we show in our article, most have a blind spot, failing to capture key ways in which subsidies send signals to markets and people. Overreliance on these models can create a false sense of certainty that misses the big picture: of course, subsidies matter to the fossil-fuel industry and help to prop it up. That is why they were introduced in the first place and why the industry and its allies continue to defend them. As the Department of Energy itself concluded 40 years ago, federal subsidies have had a "large effect" on capital formation and oil production in the U.S. And more oil infrastructure and more production mean more greenhouse gas emissions.

The public and policy makers should be under no illusions about the basic realities at stake: Holding back catastrophic global warming requires dramatically reducing fossil-fuel production. And subsidies to fossil-fuel companies undermine that goal. Once upon a time, it made sense for countries to support their fossil-fuel industries. But that time is over. SA

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Naomi Oreskes is a professor of the history of science at Harvard University. She writes the Observatory column for *Scientific American.*

Harro van Asselt is a professor of climate law and policy at the University of Eastern Finland.

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THE LAST

Can we remove enough CO_2 from the atmosphere to slow or even reverse climate change?

By Richard Conniff

Photographs by Liz Tormes

INJECTION WELLS at Iceland's Hellisheiði geothermal power plant send brine down into deep bedrock, along with carbon dioxide pulled from the air.

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RESORT

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NOT LONG AGO IT SEEMED AS IF REDUCING GREENHOUSE GAS emissions would be enough to save the world from climate change. Replace fossil-fuel power plants with clean energy sources, make cars and buildings more efficient, switch to LED lights, eat less meat. Slashing emissions and boosting renewables looked like the answer even to the Intergovernmental Panel on Climate Change as recently as 2005. But the strategy has not worked out as planned. Global emissions have gone up, not down. It now appears that even cutting annual net emissions worldwide to zero by 2050 will not be enough.

To prevent economic and environmental devastation, climate experts maintain that we will now also have to achieve *negative* emissions. Doing so means removing billions of tons of carbon dioxide from the atmosphere every year. That is like saying we can no longer put out the garbage—and we need to steadily take back the garbage we put out in the past.

Negative emissions on a massive scale have become "a biophysical requirement" to meeting climate change goals, according to a 2018 study led by Jan C. Minx of Germany's Mercator Research Institute on Global Commons and Climate Change. Figuring out how to get there is a matter of "immediate urgency," he and his co-authors warn in *Environmental Research Letters,* if the world hopes to limit warming to 1.5 degrees Celsius. Almost every nation on the planet subscribed to that target—with a fallback of "well under" two degrees C—as part of the 2016 Paris Agreement on climate change. Warming is currently about one degree above preindustrial levels. But it is increasing at 0.2 degree C per decade. In a special report in October 2018, the Intergovernmental Panel on Climate Change warned that we have just 12 years to act if we hope to avoid slipping past 1.5 degrees C, the level regarded by most scientists as the furthest we can go if we hope to preserve life more or less as we know it.

Staying under that threshold mandates a specific "carbon budget," an overall amount of carbon dioxide we can add to the atmosphere without pushing warming beyond that temperature. At today's emissions—about 40 billion to 50 billion tons a year—"there may be only five years' worth of CO_2 emissions left" in the 1.5-degree scenario, Minx and his co-authors say. (For the remainder of this article, we use "tons" to mean "metric tons.") After that, every additional ton would require an equal withdrawal. His group estimates the world will need to remove 150 billion to more than one trillion tons of CO_2 from the atmosphere by 2100—roughly two billion to 16 billion tons a year, starting in 2050, with the number increasing significantly later in the century.

To do that, Minx and his team note, we will have to start building "several hundred" carbon capture and storage installations a year beginning in 2030, just 10 years from now. That could mean deploying big machines to pull carbon dioxide from the air or developing bioenergy power plants that burn trees—grown in continuous rotation—in a facility that captures emissions and sends them deep underground for permanent burial. Low-tech options would include replanting cut forests or expanding existing ones, improving farm and pasture soils so they hold more carbon, and crushing and spreading certain kinds of rock that soak up CO_2.

Most of the higher-tech carbon capture methods are still in the early stages of development, however. They require enormous investment at considerable risk of failure and may entail major side effects, including competition for land that is already being used to feed people or provide habitat for wildlife.

Yet pursuing carbon capture on a massive scale appears to be unavoidable. When University of Washington statistician Adrian E. Raftery and his co-authors of a 2017 study in *Nature Climate Change* looked at current trends—not including negative emissions technologies—they found we are on track to reach 3.2 degrees C of warming by the end of the century, with a range from two to 4.9 degrees C. In a subsequent study in the *Proceedings of the National Academy of Sciences USA,* Texas A&M climate scientist Yangyang Xu and a colleague categorized warming greater than three degrees as "catastrophic" and greater than five degrees as posing "existential threats to a majority of the [human] population."

IN BRIEF

To limit global warming to 1.5 degrees Celsius, nations will have to remove up to one trillion tons of carbon dioxide emissions from the planet's atmosphere this century.

Finding the optimal mix of carbon capture methods will be critical. Machines that pull CO_2 from the air could remove 250 billion tons by 2100. Replanting clear-cut forests could achieve 180 billion tons.

Net costs range from $0 to $300 per ton. Unless big markets are developed to use the captured CO_2, a carbon tax may provide the best support for the techniques.

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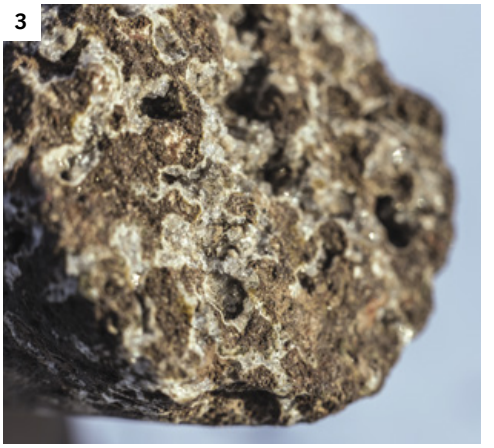

CLIMEWORKS MACHINE extracts carbon dioxide from the atmosphere (*1*). An injector inside a nearby dome (*2*) sends the gas more than 700 meters underground, where it reacts with basalt bedrock to form carbonate, visible as white streaks in a core sample from the basalt (*3*).

So let us assume that one trillion tons of negative emissions in this century—an average of 20 billion tons a year from 2050 to 2100—is necessary. What share of that pie could each method account for and at what cost? Given competition among methods for certain resources, such as land, what is the best mix to pursue? And can we muster the political will to pursue negative emissions—while drastically cutting our current carbon dioxide output?

CLEAN THE WIND

ON A HARDENED LAVA FIELD OF BOULDERS and moss in the foothills just outside Reykjavík, Iceland, a machine the size of a one-car garage pulls air through a chemical filter that extracts carbon dioxide. It is powered by waste heat from the geothermal power plant next door, and it pumps the captured carbon dioxide more than 700 meters underground, where the gas reacts with basalt rock and becomes solid mineral. Climeworks, a Swiss start-up, calls the operation the first direct air capture and storage plant in the world. It sequesters a modest 50 tons of carbon dioxide a year.

Direct air capture and storage may be the most straightforward path to negative emissions: banks of fans would harvest CO_2 from the sky and bury it. Scientific scenarios project that this technology could remove 10 billion to 15 billion tons of carbon dioxide a year by the end of the century; a few experts think 35 billion or 40 billion tons may be possible. This is such a tantalizing prospect that many climate scientists worry it could pose a moral hazard: people might think they can delay fossil-fuel reductions now in the hope of technological salvation later.

The most thorough review of removal methods—another 2018 study in *Environmental Research Letters*—takes a more sober view. Sabine Fuss of Mercator and her colleagues examined costs, side effects, environmental sustainability and other factors to project the carbon sequestration potential for seven major removal methods. Fuss and her co-authors put that potential for direct air capture in 2050 at only 500 million to five billion tons a year—adding up to 25 billion to 250 billion tons this century—at a cost of $100 to $300 per ton. For perspective, our cars each typically emit 4.6 tons of carbon dioxide a year.

Indeed, air capture "is not a silver bullet," says James S. Mulligan of the World Resources Institute's Food, Forests, and Water Program. "It's not a shiny object. It's kind of a cruddy object. But we need it." Some researchers claim they could get the cost below $100 per ton. Yet if the time line for doing that at scale is anything like the 60-plus years it took solar power to move from satellites in the 1950s to broad marketplace penetration today, Minx says "it may be too late."

Direct air capture also consumes enormous amounts of energy. Removing a million tons of carbon dioxide a year would require a 300- to 500-megawatt power plant, according to Jennifer Wilcox, a chemical engineering professor at Worcester Polytechnic Institute. If that were a coal-fired plant, it would create more emissions than it would remove. If power came from solar or wind farms, it would cover a lot of land that might already be in demand for farming or nature. And of course, a million tons would barely make a dent in the target of 20 billion tons a year.

Constructing such plants now might be essential to developing the know-how for building them on a much larger, more efficient scale later in the century. "But if you went out and built

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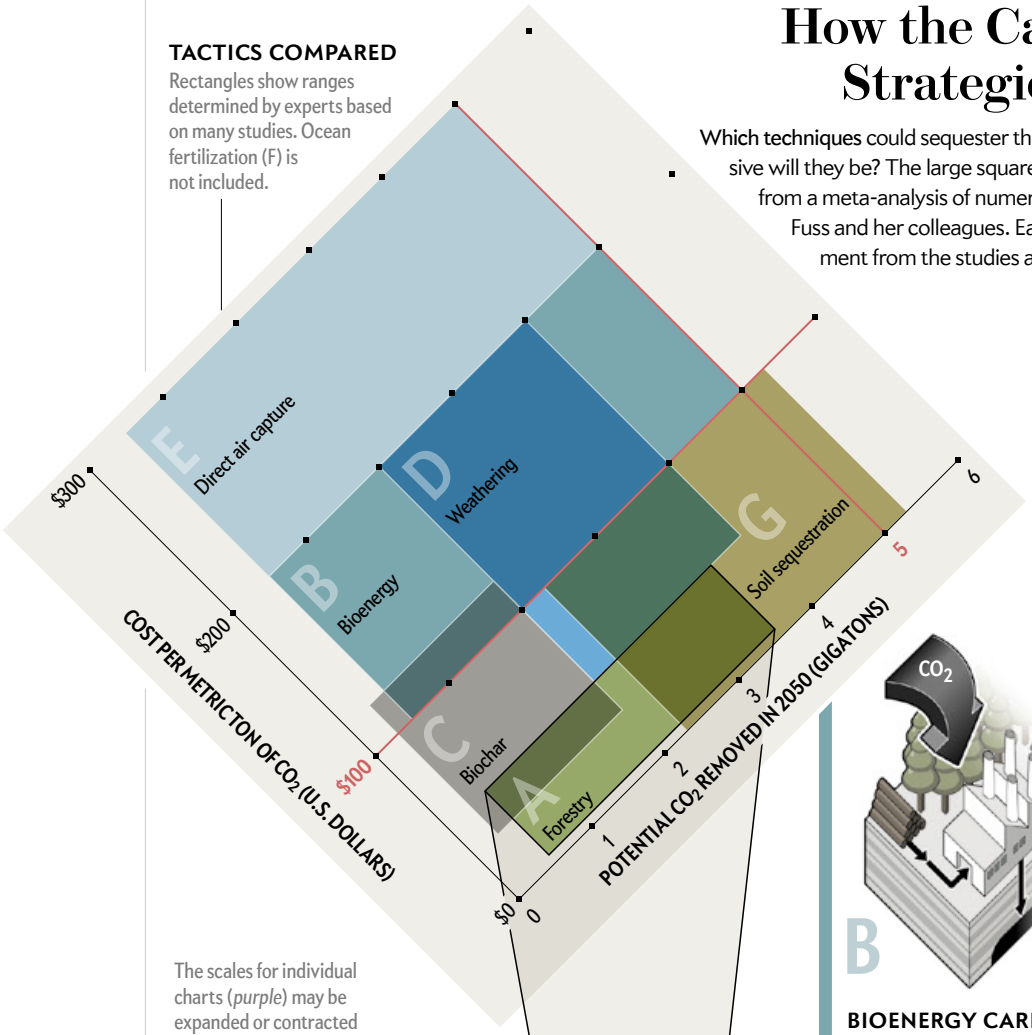
How the Carbon Capture Strategies Stack Up

Which techniques could sequester the most carbon dioxide in 2050? How expensive will they be? The large square compares approaches. The numbers come from a meta-analysis of numerous studies, performed by economist Sabine Fuss and her colleagues. Each breakout chart shows a detailed assessment from the studies and the expert judgment of Fuss's team.

TACTICS COMPARED

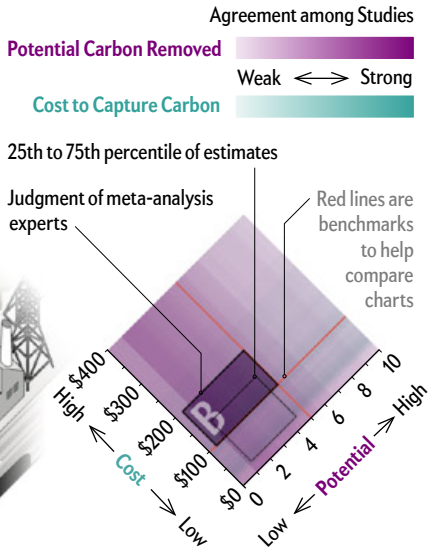
Rectangles show ranges determined by experts based on many studies. Ocean fertilization (F) is not included.



The scales for individual charts (*purple*) may be expanded or contracted for easier reading.

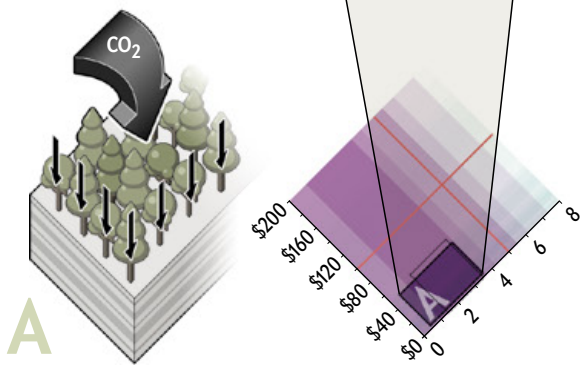
HOW TO READ THE PURPLE CHARTS

Colors depict the range of values from numerous studies. Darker shades indicate heavier overlap.



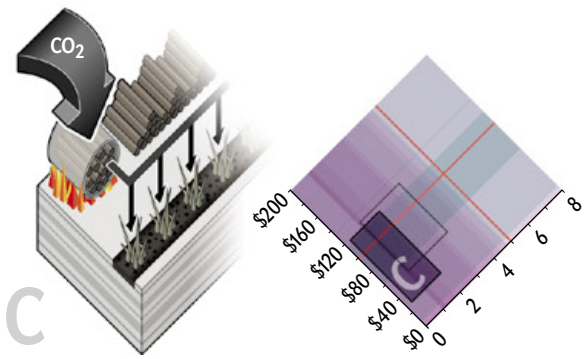
BIOENERGY CARBON CAPTURE AND STORAGE

Plants, which breathe in CO_2, are burned to produce energy or fermented into fuel. The CO_2 is removed and pumped deep underground for permanent storage. The products create revenue, but wide adoption could eat up land needed for food crops.



REFORESTATION AND AFFORESTATION

Trees are planted to replace clear-cut forests or expand existing ones. They absorb CO_2 from the air and convert it into new wood growth, including roots. Timber markets and management practices would have to be reformed.



BIOCHAR

Crops, manure or organic waste is heated, without oxygen, creating biofuel and biochar—a charcoal-like residue rich in carbon. It is spread onto agricultural fields to improve soil, which can also bind additional carbon. Large-scale production with minimal energy inputs could be a challenge.

Graphics by Pitch Interactive, Illustrations by Ben Gilliland

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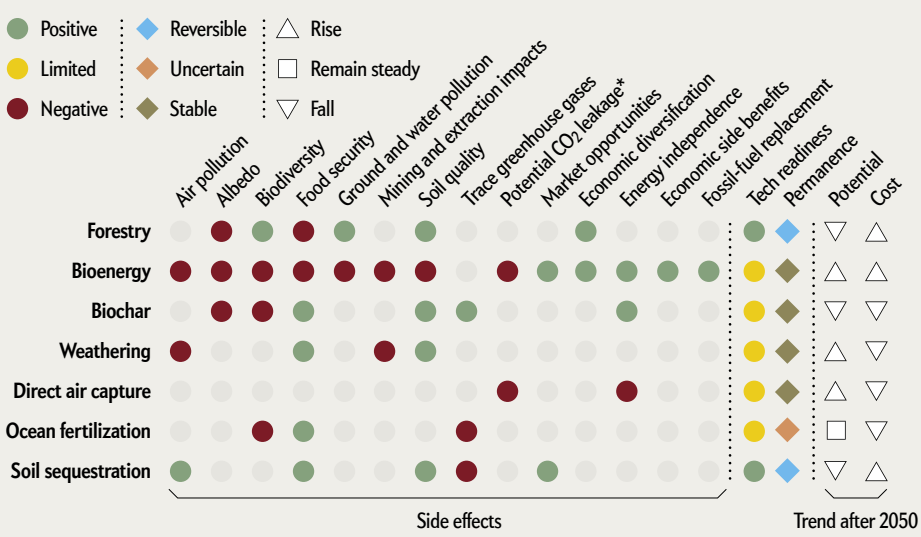
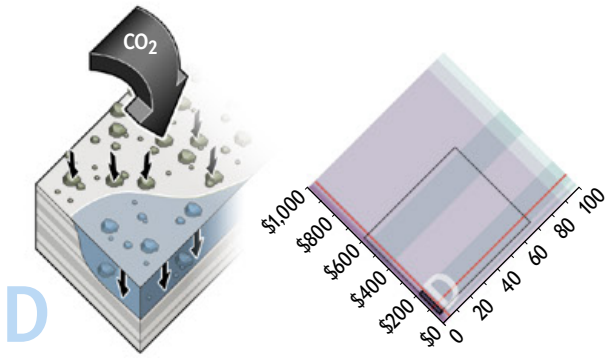


*"Potential CO_2 leakage" is from underground storage.

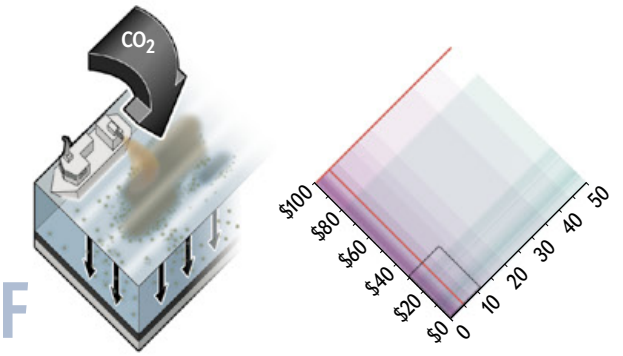
PROS AND CONS

Techniques that capture carbon in 2050 (*rows*) may come with positive or negative side effects (*dots*). The "tech readiness" column indicates how set for deployment an approach may be at that time. "Permanence" is whether stored CO_2 might escape back into the atmosphere: "reversible" indicates high risk; "stable" indicates low risk (*diamonds*). Whether the potential for sequestration or costs will rise or fall beyond 2050 is shown at the far right (*triangles*), based on factors such as land limitations. Effects are judged on how they are predominately assessed in published papers (if few papers exist, entries may be blank).



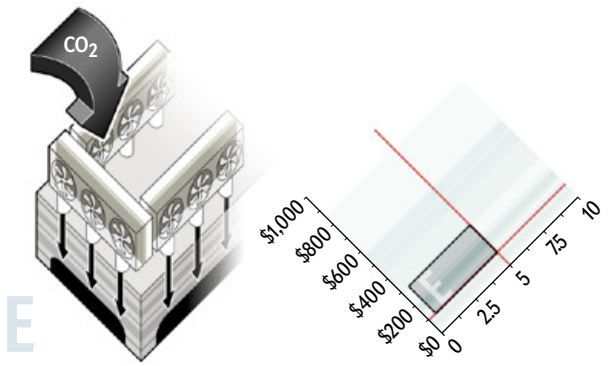
ENHANCED WEATHERING

Rock is pulverized into dust. When spread on fields, it draws CO_2 from the air and fertilizes soil. When sprinkled on the ocean, it reacts with seawater, converting CO_2 into carbonates that fall to the seafloor. Grinding and transporting rock economically are key.



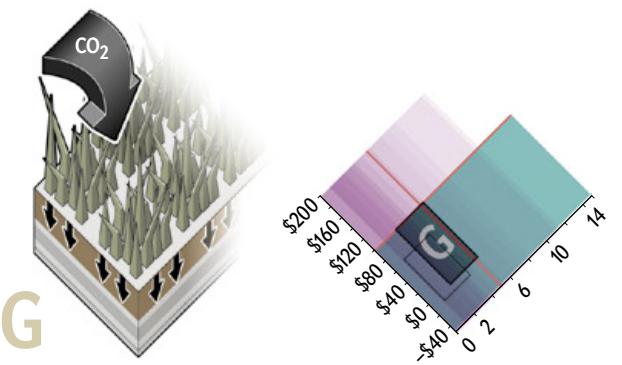
OCEAN FERTILIZATION

Iron filings are sprinkled at sea, helping plankton grow. They breathe in CO_2 and convert it into sugar or cellular material. When they die, they sink to the seafloor. Gains would be short-lived, and altering the ecosystem would be risky, so experts dropped it from the composite chart (*opposite page*).



DIRECT AIR CAPTURE

Machines pull in ambient air and chemically separate out CO_2, pumping it underground for permanent storage. Projected costs are high but could decline with technology development. (Data for "potential" were not available.)



SOIL CARBON SEQUESTRATION

Grasses or crops breathe in CO_2 and convert it into root material, fixing carbon in the soil. Soil-management techniques could enhance sequestration and plant yield. Long-term potential may be limited because soils can hold only so much carbon.

SOURCE: "NEGATIVE EMISSIONS—PART 2: COSTS, POTENTIALS AND SIDE EFFECTS," BY SABINE FUSS ET AL., IN *ENVIRONMENTAL RESEARCH LETTERS*, VOL. 13, NO. 6, ARTICLE NO. 063002; JUNE 2018

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20 million tons of direct air capture today, that would be the wrong thing to do with your money," says Roger Aines, chief scientist of Lawrence Livermore National Laboratory's energy program. "It would take a lot of solar and wind power, and if you had that much solar and wind power, the best thing to do would be to put it on the grid and turn off a coal plant." Preventing new emissions is still the overwhelming priority.

PORTFOLIO OF FIXES

THE FUSS STUDY DOES NOT simply add up the potential of the seven carbon capture methods, because some of them compete for the same resources. For example, too much reforestation would take away land needed to grow the fuel for bioenergy power plants, and too much bioenergy might compete with direct air capture for underground carbon sequestration. Climate scientists say we need to optimize a portfolio of methods.

One way to start building this portfolio, says Pete Smith, a professor of soils and global change at the University of Aberdeen in Scotland, is by scaling up "stuff we already know how to do. We know how to plant trees. We know how to restore peatlands, basically by raising the water table," so the peat captures carbon dioxide instead of emitting it. "We know how to improve soil carbon content.... Incentivizing those sorts of things is [relatively] easy and could be done immediately. It would get us some of the way there."

Consider reforestation. Tragically, the world's tropical forests have become a source, rather than a sink, for carbon dioxide emissions, as trees are cut down and burned or as ravaged forests degrade. Getting forests back into negative emissions territory would first require major reforms in an international timber market that is heavily influenced by illegal trade. Beyond that, the obvious place for reforestation is land that had been clear-cut for farming or grazing but was abandoned as unproductive. Restoring five million square kilometers of such land could sequester 3.7 billion tons of carbon dioxide a year if adequate funding were available, according to a 2015 study in *Nature Climate Change* led by Richard Houghton of the Woods Hole Research Center.

Turning all livestock grazing lands that used to be forested back into forests again could create as much as 10 billion tons of negative emissions a year, according to Bronson W. Griscom, a senior director at the Nature Conservancy and lead author of a study on "natural climate solutions" in *PNAS*. That is a sizable portion of the annual carbon dioxide recovery needed annually. But the move would require a global shift away from meat eating, the opposite of the current trend.

Fuss and her co-authors foresee more modest potential. Trees live and die, meaning they will store carbon now but give it up again later this century or the next. The amount of carbon dioxide sequestered will also likely decline as forests mature, growing more slowly. Wildfires, deforestation and climate change raise the risks. Even so, forest expansion could provide a critical stopgap while direct air capture or other technologies are scaling up. Fuss puts the potential somewhere between 500 million and 3.6 billion tons of carbon dioxide removal a year by midcentury. That could take 25 billion to 180 billion tons off our target of one trillion tons this century, at a cost of $5 to $50 per ton.

Better management could raise the gains. Griscom notes, for example, that tree plantation managers in the southeastern U.S. knowingly harvest loblolly pine trees several years before their optimal yield. Allowing them to sell carbon credits to cover the extra years of growth could delay harvesting to the optimal age, adding on more timber and more carbon storage. Likewise, growing nitrogen-fixing plants in pastures and moving to a smarter system of pasture rotation could make grazing more productive while improving carbon storage in soils. Fuss conservatively estimates that improvements in soil sequestration can yield up to 5.3 billion tons a year—265 billion tons this century—at $0 to $100 per ton.

BIOCHAR fertilizer was made by heating chicken waste and wood chips that would otherwise emit carbon dioxide as they decay.

JEFF HUTCHENS *Getty Images*

That would be in addition to biochar. In this form of carbon removal, a specialized furnace applies heat in the absence of oxygen to biomass, turning it into a form of charcoal and generating useful by-products such as bio-oil or synthetic gas. When the charcoal is applied to farm fields, it binds carbon in the soil and can improve crop yields. But no one has yet attempted to deploy biochar on a large scale. Fuss and her co-authors consider it a plausible source of 300 million to two billion tons of annual carbon dioxide removal, at $90 to $120 per ton. That is 15 billion to 100 billion tons in this century.

Another land-based approach is called bioenergy with carbon capture and storage, or BECCS. Early plans from many countries for meeting their Paris commitments depend on it, yet it is deeply controversial. A power plant burns wood, agricultural wastes or other biomass such as switchgrass. These sources take carbon dioxide out of the atmosphere as they grow or accumulate. Combustion releases it again, and the power plant recaptures it from the smokestack, sending it down into deep geologic formations for permanent storage. But reforestation for biofuel production at the scale suggested by some proponents could eat up much of the world's arable land, threatening food production and nature conservation, as well as carbon dioxide removal by other methods such as reforestation or soil sequestration. Pulling emissions from the smokestack also sharply reduces power plant efficiency, at least with current technologies. Hence, Fuss puts the sustainable yield from BECCS at just two billion tons a year, well below the forecast by other researchers, at a cost of $100 to $200 per ton. Fuss's estimate would account for 100 billion tons of negative emissions by 2100.

That leaves two other carbon capture methods now under consideration. Enhanced weathering exploits a natural process: carbon dioxide in the air converts into carbonate when exposed to

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certain kinds of crushed rock. The question is whether researchers can find a way to grind the right rocks into powdered form economically, to speed up the natural process. Fuss puts the potential at two billion to four billion tons a year, at $50 to $200 per ton. Her team concludes that ocean fertilization—sprinkling iron or other nutrients into the ocean to stimulate growth of algae and other plankton, which take up carbon dioxide—would be too inefficient and short-lived to justify potential ill effects on ecosystems. It is "not a viable negative emissions strategy," they write.

PROFIT RATHER THAN COST

WHERE DOES THE ACCOUNTING LEAVE US? The ranges in the Fuss study add up to as little as 150 billion tons or a bit more than one trillion tons by 2100. The latter number might sound as if it solves our problem. But we cannot just add up the numbers because of conflicts between methods. What we can do, Fuss says, is manage the portfolio to take advantage of beneficial overlaps. Enhanced weathering, for instance, could be deployed on the same land being used to grow biomass for BECCS.

What all the approaches need, scientists argue, is massive investment in research and development. "This is going to be a long, hard battle," says Lawrence Livermore's Aines. But governments have been reluctant to foot the bill for negative emissions technologies because of ideological resistance to "picking winners" and because some past investments have been notorious failures. The U.S. Department of Energy, for instance, has spent huge sums of money on carbon capture projects intended to make "clean coal" power generation a reality. Southern Company abandoned the latest attempt in 2017, switching the Kemper County clean coal plant in Mississippi to natural gas after spending $7.5 billion.

A carbon tax would bypass picking winners by imposing a cost on emissions—a cost for putting garbage into the atmosphere. That would create a marketplace motivation both to reduce emissions now and to claw back past emissions later. The U.K. imposed such a tax, currently at about $25 per ton, primarily on fossil-fuel power plants, which cut coal emissions in half just from 2015 to 2016. Most governments shy away, however, seeing a tax as too drastic for economies built on fossil fuels.

With few exceptions, corporations have also been reluctant to invest in CO_2 removal technologies because, until recently, they saw no marketplace. To them, fixing the climate is a public benefit, not something from which they can earn a profit. But that may be changing because of a surprisingly bipartisan package of tax incentives approved by the U.S. Congress in early 2018. The so-called 45Q legislation significantly increases the tax credits companies can claim over the next 12 years, not just for capturing carbon dioxide and sequestering it underground—at as much as $50 per ton in tax credits—but for using CO_2 in a variety of ways.

The most controversial use is "enhanced oil recovery." An oil company purchases carbon dioxide, transports it by pipeline and injects it into depleted oil wells, pushing out extra oil it could not extract by conventional means. A climate change solution that entails producing *more* fossil fuels may sound Orwellian, and some environmental critics have attacked 45Q as just another fossil-fuel subsidy program in disguise. But enhanced oil recovery appears to reduce current emissions because the captured carbon dioxide, typically from natural gas or ethanol refineries, gets sequestered underground. Some environmentalists, such as Kurt Waltzer of the Clean Air Task Force, argue that turning carbon capture into an energy technology, rather than an emissions technology, is the first step toward broad commercial adoption of carbon dioxide removal. It turns recaptured CO_2 into a product to be bought or sold rather than simply a cost to be endured. That could be the key to eventual negative emissions.

TIME TO START

COULD A PORTFOLIO OF CARBON capture methods, taxes and markets get us to the goal of one trillion tons by 2100? The record-breaking temperatures of 2018 and 2019 may have been a turning point. The American West was on fire. People on four continents experienced severe heat waves. In Japan, thousands of heatstroke victims went to the hospital in a single week. Even the Arctic experienced a major heat wave, and 3,500 square miles of Amazon forest went up in flames, darkening the skies over São Paolo. Climate scientists shook off cautious language and warned, in *PNAS,* that further warming risks tipping the planet into a "Hothouse Earth ... likely to be uncontrollable and dangerous to many." Tens of millions of people took to the streets in 150 countries as part of a worldwide climate strike. In case that message was not strong enough, senior author Hans Joachim Schellnhuber, director emeritus of the Potsdam Institute for Climate Impact Research in Germany, told reporters that the cascading effects could lead to a world capable of supporting just one billion human beings, down from 7.5 billion today.

For some political leaders even now, climate change still seems shrouded in uncertainty, despite the overwhelming evidence that it is our grim present and grimmer future. The disconcerting thing about negative emissions technologies is that so much can seem uncertain even for the scientists themselves. "Everyone is talking about how it depends on what the substrate is, what part of the world you're in, what the rainfall is like there and what the temperature is," says University of Virginia ecologist Stephanie Roe, speaking about soil carbon enhancement. Likewise, carbon sequestration in forests began to look far less certain as apocalyptic wildfires burned across Australia.

Researchers also get caught up in arguing about whether any of the carbon removal methods, much less all of them, can scale up to billions of tons annually. "There's maybe a bit too much focus in this debate about what's the eventual scale," says Brendan Jordan of the Great Plains Institute in Minneapolis. "I fear that it paralyzes us, and we really can't afford paralysis." That is, we need to start to achieve negative emissions despite uncertainties because they are trivial compared to a world in which the climate change game of musical chairs stops, and there's no room for 6.5 billion people to sit down. SA

Richard Conniff is an award-winning science writer. His books include *The Species Seekers: Heroes, Fools, and the Mad Pursuit of Life on Earth* (W. W. Norton, 2011).

MORE TO EXPLORE

Natural Climate Solutions. Bronson W. Griscom et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 114, No. 44, pages 11,645–11650; October 31, 2017.
Negative Emissions—Part 2: Costs, Potentials and Side Effects. Sabine Fuss et al. in *Environmental Research Letters,* Vol. 13, No. 6, Article No. 063002; June 2018.
Technological Carbon Removal in the United States. James Mulligan et al. World Resources Institute, September 2018.

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WHAT SHOULD CARBON COST?

Smart math, combined with fundamental policy choices, can determine a practical tax that will drive down CO_2 emissions

By Gilbert E. Metcalf

Illustrations by Katie Edwards

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ASK ANY ECONOMIST HOW WE SHOULD RESPOND TO CLIMATE CHANGE, and they will tell you that the most effective strategy is to put a price on greenhouse gas emissions, ideally through a carbon tax. This reflects a basic economic principle: the waste produced from any activity is a cost that has to be paid. We pay for throwing away our garbage, for cleaning our wastewater, and we should pay for the carbon dioxide waste we create from activities such as burning fossil fuels.

IN BRIEF

Economists agree that a carbon tax is the most effective way to reduce carbon dioxide emissions. But taxes passed by certain countries range wildly from less than $1 to $121 per ton. In the U.S., models seem to converge at $40 to $47. ("Ton" refers to "metric ton.")

The key is calculating the social cost of carbon. That requires a discount rate on investments, knowing the damage CO_2 emissions will impose on the economy, and the risk of potential disasters.

When setting a tax rate, policy makers may factor in revenue generation, specific emissions-reduction targets or insurance against catastrophe.

We can put a price on our pollution with a carbon tax or with a cap-and-trade program, as European countries have done for power plants and industry. Cap and trade sets an overall limit on emissions (the cap). Firms with low costs of reducing emissions cut their releases and sell allowances to firms with high costs, which continue emitting, while the set of participants stays within the limit. But prices in cap-and-trade arrangements have proved to be volatile, and the systems need strong oversight to avoid problems.

Why bother? A carbon tax provides greater clarity about the price of emissions, which the business community values. And the U.S. already has a well-developed tax collection system, which works smoothly for collecting excise taxes on many fossil fuels.

For reasons like these, economists such as Gregory Mankiw, former head of the U.S. Council of Economic Advisers under President George W. Bush, have prominently supported a carbon tax. The bipartisan Climate Leadership Council, an international policy institute, published a statement in 2019 that argues that "a carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary." As of this writing, the statement is signed by 3,589 economists—including the three living former chairs of the Federal Reserve, 27 Nobel laureates and 15 former chairs of the Council of Economic Advisers. How the U.S. addresses climate change has become a major topic in the presidential campaign, and there are eight bills in Congress, one with 80 co-sponsors, to put a price on our carbon pollution.

Still, enacting a carbon tax will be a big political lift. If a window does open for it, climate scientists, economists and politicians need to be ready to pounce. They will need to get it right the first time. And they will need to explain why a specific tax rate is justified.

Determining that rate seems to be straightforward: set the tax per ton of CO_2 equal to the damage inflicted by its release. But how do we properly assess the damage?

HARM FROM EMISSIONS

ECONOMISTS TYPICALLY CALCULATE climate damages with integrated assessment models (IAMs)—large computer models that capture feedbacks between the economy and the climate. They use a series of equations that characterize the global economy, the worldwide circulation of CO_2 emissions arising from economic activity, and damages resulting from atmospheric and upper-ocean temperature increases. IAMs are so important that in 2018 the Nobel Prize in economics was awarded to Yale University economist William D. Nordhaus, for his pioneering work on them.

IAMs such as Nordhaus's dynamic integrated model of the climate and economy (DICE) have become influential in policy analysis. The Obama administration used three IAMs, including DICE, to determine a dollar value that government should use in cost-benefit analyses for proposed new regulations, including the 2011

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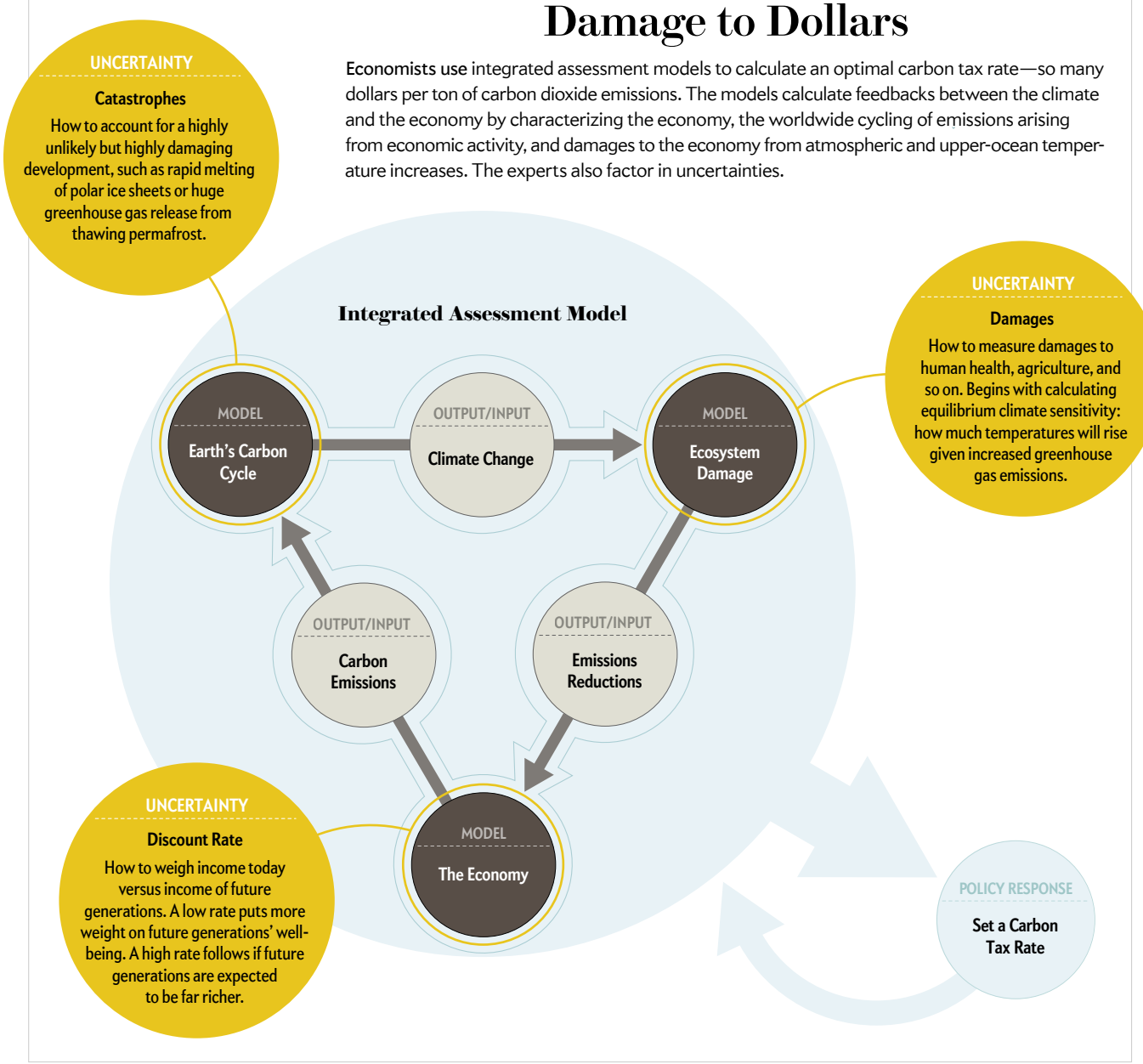
Damage to Dollars

Economists use integrated assessment models to calculate an optimal carbon tax rate—so many dollars per ton of carbon dioxide emissions. The models calculate feedbacks between the climate and the economy by characterizing the economy, the worldwide cycling of emissions arising from economic activity, and damages to the economy from atmospheric and upper-ocean temperature increases. The experts also factor in uncertainties.


UNCERTAINTY
Catastrophes
How to account for a highly unlikely but highly damaging development, such as rapid melting of polar ice sheets or huge greenhouse gas release from thawing permafrost.
Integrated Assessment Model
MODEL
Earth's Carbon Cycle
OUTPUT/INPUT
Climate Change
MODEL
Ecosystem Damage
UNCERTAINTY
Damages
How to measure damages to human health, agriculture, and so on. Begins with calculating equilibrium climate sensitivity: how much temperatures will rise given increased greenhouse gas emissions.
OUTPUT/INPUT
Carbon Emissions
OUTPUT/INPUT
Emissions Reductions
MODEL
The Economy
UNCERTAINTY
Discount Rate
How to weigh income today versus income of future generations. A low rate puts more weight on future generations' well-being. A high rate follows if future generations are expected to be far richer.
POLICY RESPONSE
Set a Carbon Tax Rate

tightening of automotive fuel-economy standards.

The models seem to answer the question of how to set the right carbon tax rate. But the damage estimates depend on pinning down several assumptions that have great uncertainty. Three challenges stand out. The first is weighing income today against the income of future generations; for that we need a discount rate, a number that is also important to many policy decisions, such as setting the Social Security tax or funding large infrastructure projects. The second challenge is measuring the damages from our CO_2 emissions. Third is how to factor in the possibility of low-probability, high-damage outcomes—so-called catastrophes.

Estimates for the optimal tax rate can vary widely depending on how these factors are treated. In the end, IAMs can give us a solid starting point for a U.S. carbon tax, but the models disagree on the "right" number. Moreover, we have to consider societal and political pressures. Those influences can be huge: 15 European countries have already set carbon taxes, and they range from $2 to $96, with a couple outliers at less than $1 and one at $121.

SOCIAL COST OF CARBON

THE IDEA of using a tax to pay for social damages dates back more than 100 years. The influential University of Cambridge economist Arthur C. Pigou maintained that if pollution creates a cost (damage) for someone

Graphic by Jen Christiansen

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that is not paid by the polluter, then government should impose a tax on the polluting activity equal to the damages. Pigou, in effect, gave Adam Smith's so-called invisible hand a green thumb.

Burning one ton of coal, for example, produces roughly two tons of carbon dioxide, by combining carbon atoms with oxygen in the air. If the damages from each ton of carbon dioxide equaled, say, $50, then Pigou's prescription would be to levy a $100 tax per ton of coal. In that way, the cost of coal would include the cost to society of burning it: the social cost of carbon (SCC). To estimate this cost, we need an IAM. Enter Nordhaus.

Nordhaus published his first paper about the DICE model in 1992. It estimated that in 2015 the SCC would be $4.54 per metric ton of carbon dioxide. When 2015 came around, and after updates to the model, he raised his estimate to $31. Assuming optimal policy, the SCC would grow to just over $100 per ton by 2050 and to $265 by 2100. (All those numbers are in 2010 dollars.)

A U.S. CARBON TAX OF $40 PER TON THAT INCREASES 5 PERCENT EACH YEAR WOULD PUT THE COUNTRY WELL ON TRACK TO BECOMING CARBON-FREE BY MIDCENTURY.

These estimates are in the middle range among major IAMs. For example, when the Obama administration estimated the SCC for assessing new regulations, it used the DICE model, along with two other well-known models: FUND and PAGE. The 2050 estimates from the FUND model were about half those of the DICE model, and estimates from PAGE were nearly double.

These numbers sound solid, but Massachusetts Institute of Technology economist Robert Pindyck argues that IAMs are useless because they are surrounded by too much uncertainty. His view is extreme, but we do need to take seriously the issues he and others have raised. Let us examine the three key IAM assumptions that can greatly impact the SCC: the discount rate, the damage function and potential catastrophes.

DISCOUNTING FUTURE GENERATIONS

ANY DECISION involving costs and benefits that are separated in time requires a discount rate. Consider an asset that will pay me $1,000 in 10 years. How much is that asset worth today? Assume I could put some money in an account that pays interest of 3 percent a year. With compounding, $744 invested today would grow to $1,000 in 10 years. In other words, the value of $1,000 in 10 years is $744 today. More precisely, the present discounted value of $1,000 in 10 years is $744, when discounted at 3 percent.

When governments need to choose a discount rate, they sometimes use the return people expect for investing in the marketplace. The U.S. Office of Management and Budget, for example, generally recommends a 7 percent discount rate for assessing government regulations because it is the approximate return on investment in the private sector in recent years.

For long-lived projects, the difference between a 7 percent discount and a 3 percent discount is huge. The present discounted value of $1 million in 250 years is 4.5 cents today at 7 percent. The value is $618 today at 3 percent. The higher the discount rate, the less we should be spending today to reduce future emissions.

Discounting at 7 percent seems reasonable for government projects that last for five to 15 years, but it is not reasonable for climate-related actions, where the benefits from today's investment could last for 200 years or more. But because people do not typically make 200-year investments, there is no relevant market rate to go by. That is true even for government-led infrastructure investments. Most of these projects, for example, the Erie Canal, have useful lives of 50 to 100 years before they need to be rebuilt or are abandoned because of innovation—in the canal's case, by railroads, then highways.

If market rates are not a good guide, perhaps we can use economic theory. Economist Frank Ramsey, a peer of Pigou, argued that the discount rate for long-term outlooks should take into account two considerations. The first reflects an ethical decision about how to treat different generations. This leans toward a low discount rate, on the grounds that we should not treat future generations differently than we do our own. Second, the discount rate should take into account changes in income over time; the richer future generations are compared to us, the less we should feel compelled to incur costs now to make them better off. That leans toward a high discount rate.

In 2006 British economist Nicholas Stern wrote a review of climate change for the U.K. government, taking both these factors into account. His so-called Stern Review concluded that the correct discount rate for climate policy was 1.4 percent. At that rate, $1 million in 250 years is worth nearly $31,000 today, far more than the $618 calculated using a 3 percent discount rate. Given his calculations, Stern argued that the costs of climate change were five times the costs of cutting emissions. The Stern Review was highly influential around the world in shaping the narrative about the need to make dramatic and rapid reductions in emissions now.

As a practical matter, we have to square approaches that lead to high and low discount rates. One resolution is that a discount rate should not remain constant over time; it should decline. If uncertainty about future income grows greater the further we go into the future, for example, then we need a precautionary

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factor. The late Harvard University economist Martin Weitzman argued that a discount rate of 4 percent should be used in the near term, whereas 1 percent should be used for the distant future (76 to 300 years), with a gradual decline for time periods in between.

In the end, economists do not have clear guidance on the "best" discount rate, in part because of the ethical choices involved across generations. Small changes in the discount rate, however, can lead to large changes in the SCC—an important factor in setting a carbon tax.

UNCERTAIN DAMAGE

THE SECOND UNCERTAINTY in setting a price on carbon is the damage CO_2 emissions will impose on the economy. In the DICE model, damages are, roughly speaking, a function of the square of the temperature increase. This approach is a shorthand for the complex impacts of warming, such as lower agricultural productivity, higher death rates from heat and diseases, loss of species, geopolitical risks such as drought-driven human migrations, and so on.

Nordhaus, like other IAM modelers, based his damage function on a review of the existing literature. This is good news because scientists have made great progress in measuring the damages from climate change. But no one can capture all possible injury. To compensate, Nordhaus increased his damage estimates by one quarter. His function leads to worldwide damages equal to 8.5 percent of global income for a planetary temperature increase of six degrees Celsius. In contrast, U.S. gross domestic product fell by more than 25 percent during the Great Depression from 1929 to 1933.

Scientists have a way to quantify the likelihood of a big temperature rise. In 1896 Swedish chemist Svante Arrhenius used a series of detailed measurements to estimate that doubling the atmospheric CO_2 concentration would warm Earth by four degrees C. This relation, now known as the equilibrium climate sensitivity, has proved remarkably durable. Unfortunately, little progress has been made in narrowing the uncertainty around it. The Intergovernmental Panel on Climate Change's Fifth Assessment Report (the most recent) states that equilibrium climate sensitivity is "likely in the range 1.5° C to 4.5° C, extremely unlikely less than 1° C, and very unlikely greater than 6° C." But the swing in damages between 1.5° C and 4.5° C is huge. IAM modelers can deal with this kind of uncertainty by making thousands of model runs, varying key parameters. They then report central estimates, and upper and lower bounds, to give policy makers a sense of the uncertainty around SCC values.

This is not entirely satisfactory. Weitzman said there is a "worrisome amount of probability" that equilibrium climate sensitivity could be above 4.5 degrees C. This enters the realm of extreme consequences.

THE PRICE OF CATASTROPHES

CATASTROPHES are low-probability, high-damage events. Weitzman cited a long litany of the "known unknowns" that could lead to catastrophes, such as rapid sea-level rise from quick melting of the Greenland and West Antarctic ice sheets or from significant changes in ocean-circulation patterns. He also considered "unknown unknowns," such as runaway climate feedbacks we have not yet identified. One example might be that warming thaws all permafrost on Earth, which releases huge amounts of CO_2 and methane, creating runaway heating. This is not just academic talk. Investment firm JPMorgan Chase recently released a report to bank clients that warns, "We cannot rule out catastrophic outcomes where human life as we know it is threatened."

On a graph, a normal distribution of the likely rise in temperature would look like a hump: a low tail at the left (unlikely), leading to a high hump in the middle (most likely), and a low tail on the right (unlikely). As our knowledge improves about how the climate is responding to our emissions, we can refine

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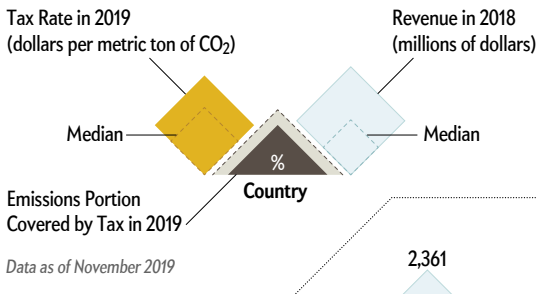
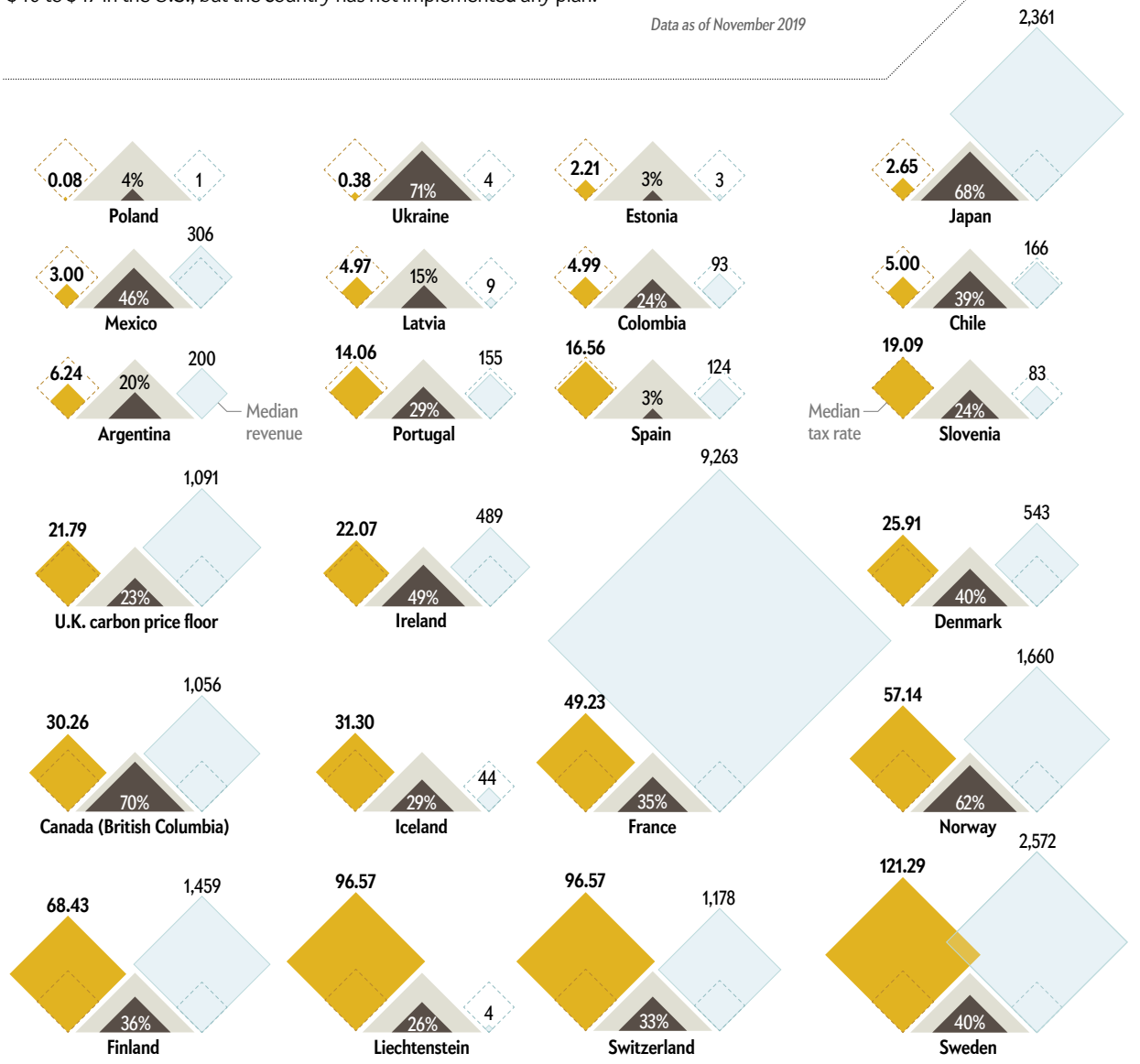
Crazy Quilt of Carbon Taxes

Two dozen countries have enacted carbon taxes, with rates ranging widely from $0.08 in Poland to $121 in Sweden. All the countries apply the tax only to a percentage of their total emissions, and some tax emissions only from certain types of fossil fuels. Political pressures most likely explain the disparities. Leading models suggest a tax of $40 to $47 in the U.S., but the country has not implemented any plan.





this distribution. It appears that the distribution will be "fat-tailed," meaning the probability of very large temperature increases (the tail to the right) goes to zero more slowly than in a normal distribution. This creates a fundamental problem for IAMs, which Weitzman called the Dismal Theorem: society should be willing to pay an infinite amount to avoid low-probability, high-damage events because expected damages are infinite. Clearly, society cannot do that.

Weitzman was not quite sure what to make of his theorem. He argued that researchers should focus more on understanding catastrophic events, to reduce our uncertainty about their likelihood and consequences. That knowledge can better inform policy choices required to respond appropriately to possible catastrophes.

SOURCE: WORLD BANK GROUP

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HOW TO PROCEED

IN THE MEANTIME, we need to determine the SCC and carbon tax rate. Uncertainties about the discount rate, damages, climate sensitivity and possible catastrophes mean that any estimate of the SCC is uncertain. The only thing we can say for sure is that the SCC must be greater than zero; any pollutant incurs a cost. It is heartening to see greater collaboration between economists and scientists—signaled by the science journal *Nature* appointing an economics editor—because it will lessen such uncertainties.

For policy makers, IAMs can provide a starting point for setting a schedule of carbon tax rates for the next few decades. For example, the three models the U.S. government used in 2016 for analyzing potential regulations gave a range of estimates for the SCC in 2020. Assuming a 3 percent discount rate, Nordhaus's DICE model suggested a mean 2020 tax rate of $47 per metric ton of carbon dioxide. Mean estimates from the other two models were $23 and $84.

Nordhaus's rate is very close to the $40 per ton rate suggested by the Climate Leadership Council. It is also close to the average initial tax rate in the seven carbon tax bills filed in Congress. In its base case, the council's tax rate would increase 5 percent each year, leading to a tax of $65 in 2030 and $173 in 2050. An economic model from Stanford University and Resources for the Future suggests that the Climate Leadership Council's proposal would create an immediate 18 percent reduction in emissions and a 50 percent reduction by 2035, relative to a U.S. economy without a carbon price. This would put the country well on track to becoming carbon-free by midcentury.

The tax would also generate a lot of revenue for the federal government. A U.S. Treasury study estimated that a carbon tax of this magnitude would raise more than $1.5 trillion over the next decade, after accounting for losses in business and related tax revenues from the tax. Focusing on revenue is a fiscal argument for a tax that might appeal to congressional policy makers who, at some point, will need funds to close a spiraling budget deficit. Or the revenue could pay for some of the zero-carbon infrastructure called for in the Green New Deal. Such an approach focuses on a carbon tax's role as a fiscal instrument more than as an environmental instrument. The government could also give carbon tax revenues back to households through a "carbon dividend," as the Climate Leadership Council has proposed.

A different strategy would focus on emissions reductions, not revenue potential. After all, taxing CO_2 will not actually guarantee a given emissions reduction, even though raising the cost of emissions will definitely drive them down. Economists, for example, have run a model of the U.S. economy that indicates a $43 tax per ton starting in 2019 would have been sufficient for the U.S. to meet the Paris Agreement goal of a 28 percent emissions reduction by 2025.

Alternatively, a carbon tax could be viewed purely as an insurance policy against catastrophes. The tax would not eliminate the risk but would help reduce it. We could call this the Grand Canyon effect. If I stand at the edge of the Grand Canyon taking in the view, there is a risk that a sudden wind gust could cause me to lose my balance and fall over the edge. By taking a step back, I reduce that risk. By slowing the rate of emissions, we reduce the risk of a catastrophic climate event.

A hybrid approach would set a tax on CO_2 and periodically update the tax rate depending on how much progress the U.S. is making toward reducing emissions. But updating is problematic. Enacting a carbon tax is going to be a political fight for Congress. Once done, Congress is unlikely to have the appetite to periodically reopen the debate by reviewing and adjusting tax schedules. We can get around that by including a "policy thermostat" in the initial legislation. For example, the legislation could include explicit emissions-reduction targets over 10 and 20 years and a process for adjusting the tax rates automatically if the country is not on track to hit those targets. A number of the U.S. carbon tax proposals use this approach.

If the U.S. moves forward with a carbon tax, it has to consider important design issues: What to do with the tax revenue. What to do for workers in carbon-intensive sectors of the economy. How to incentivize carbon capture and sequestration. Whether to tax the carbon dioxide embedded in imported goods. And whether there is a political trade-off to be had in relaxing some environmental regulations in return for a carbon tax.

Additional policies will be needed, too. Certain greenhouse gas sources may not be amenable to taxation and might be more cost-effectively addressed through regulation. One example is methane emissions from oil and gas fields. Trying to measure and tax them is unrealistic; requiring technologies that reduce the leakage is more effective. More fundamentally, we will need more funding for R&D to invent and bring to market affordable zero-carbon energy technologies and perhaps cost-effective carbon capture and storage technologies.

Putting a price on our emissions now is essential. Here is a simple reason why: 2019 was the second hottest year on record worldwide, and the past five years were the hottest of the past 140. SA

Gilbert E. Metcalf is a professor of economics at Tufts University who specializes in climate economics. He is a research associate at the National Bureau of Economic Research and author of *Paying for Pollution: Why a Carbon Tax Is Good for America* (Oxford University Press, 2019).

MORE TO EXPLORE

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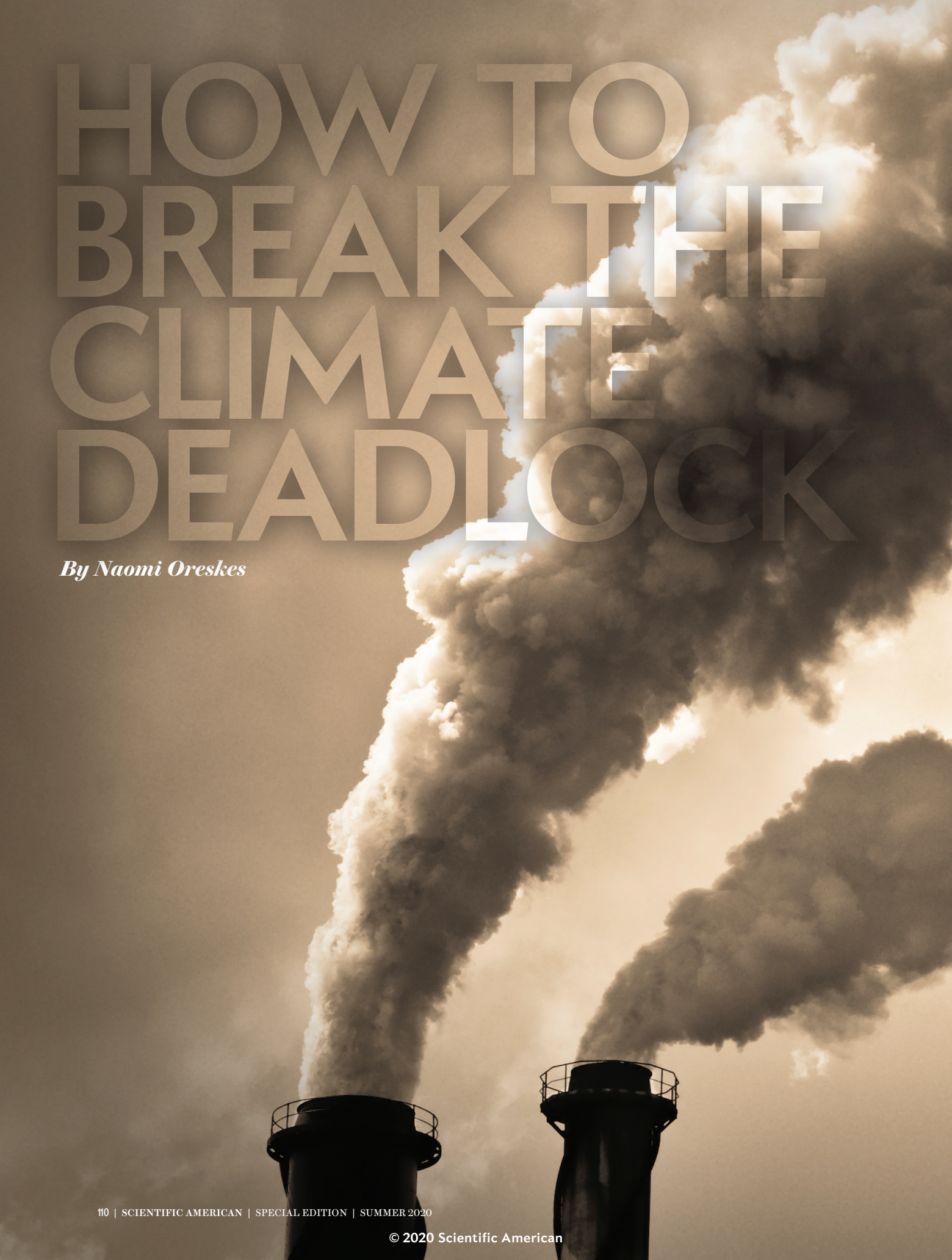
HOW TO BREAK THE CLIMATE DEADLOCK

By Naomi Oreskes



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WILL NATIONS EVER COME TOGETHER TO KEEP CLIMATE OUT OF THE SEVERE DANGER ZONE? The question looms like a cloud now that President Donald Trump is withdrawing the U.S. from the Paris climate change accord—an international agreement to curb greenhouse gas emissions. But the nation's ambivalence about climate change long predates the last presidential election. A major reason is some American conservatives' hostility to government intervention. If the U.S. and the world are to succeed in limiting disruptive climate change, the U.S. will have to give up the idea that free markets alone can adequately address climate change and accept the reality that markets need help from governments.

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A UNITED NATIONS TREATY IS EFFECTIVE only if signatory nations are prepared to follow suit with firm domestic policies, but American politicians have resisted action, afraid of paying a political price. The rejection of climate action is largely based on suspicion of big government, and an international treaty is government at its biggest. Yet making a substantial impact on something so fundamental as the sources of energy that drive our civilization is going to require billions (if not trillions) of dollars of investments and incentives that span diverse industries—the kinds of actions that the private sector has historically not made. If nations are ever going to put the brakes on climate change, the U.S. will have to overcome its aversion to government playing a major role.

UNREASONABLE RELIANCE ON FREE MARKETS

IT HAS LONG BEEN a maxim in American life that the government that governs best governs least. It was expressed in the weakness of the original Articles of Confederation, in the structure of the U.S. Constitution (designed to prevent the concentration of power) and at various times throughout U.S. history. In the 20th century it was an important element in reactions against federal labor standards, rural electrification and, especially, the New Deal, the spectacular government intervention that followed the equally spectacular market failure of the Great Depression. The deal empowered the federal government with substantive oversight of business, industry, and financial and labor markets. But the opponents of the New Deal never denied the fact of the Depression.

Opponents of an international treaty on climate change have allowed their hostility to government not only to lead them to discount the facts of climate change but also to spill over into conspiratorial thinking. In a 1992 speech Dixy Lee Ray, a former governor of Washington State and a former head of the U.S. Atomic Energy Commission, insisted that the agenda of the U.N. Framework Convention on Climate Change was to "bring about … world government with central planning by the United Nations." The flame she lit has burned brightly ever since. In his 2012 book Senator James Inhofe of Oklahoma accused climate scientists of being part of a liberal conspiracy to dismantle global capitalism and compared the Environmental Protection Agency to the Gestapo. Trump has a conspiracy theory of his own, having called climate change a hoax perpetrated by the Chinese.

Trump's views may be extreme, but they reflect a greater conservative mindset. In our 2010 book, *Merchants of Doubt,* Erik M. Conway and I show how conservative and libertarian think tanks have questioned the scientific evidence of climate change under the rubric of defending freedom, which they equate with laissez-faire capitalism: low rates of taxation, minimal regulation of business, and little or no government intervention in the marketplace. Social scientists have also shown a strong correlation between "free market ideology" and the beliefs that global climate change is not occurring, is not human-caused or will have positive effects—all positions that contradict the findings of the global scientific community.

IN BRIEF

American rejection of climate action is based on suspicion of big government, often expressed as a threat to freedom.
Free markets will not solve climate change by themselves; they have failed to account for the damage done by carbon emissions to people and the environment.
A carbon tax, or emissions-trading system, could slow climate change, but government is needed to create those systems.
History shows that government is also needed to create and fund major technological innovations of the scale required to solve climate change. For that to happen, Americans will have to stop demonizing government.

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The main claim of politicians, lobbyists and CEOs who lead the charge to minimize the government's role in addressing climate change is that the world should rely on the marketplace to fix the problem. Greenhouse gas emissions are part of the world's economy, so if they are a problem, markets will respond, for instance, by offering technologies to prevent climate change or allow us to adapt to it.

In truth, however, energy markets do not account for the "external," or social, costs of using fossil fuels. These are not reflected in the price we pay at the pump, the wellhead or the electricity meter. For example, pollution from coal causes disease, damages buildings and contributes to climate change. When we buy electricity generated from coal, we pay for the electricity, but we do not pay for these other real, measurable costs.

INDUSTRY confers economic benefits but imposes social costs; science and government must balance the two.

In a properly functioning market, people pay the true cost of the goods and services they use. If I dump my garbage in your backyard, you are right to insist that I pay for that privilege, assuming you are willing to let me do it at all. And if you do not insist, you can be pretty sure that I will keep on dumping my garbage there. In our markets today, people are dumping carbon dioxide into the atmosphere without paying for that privilege. This is a market failure. To correct that failure, carbon emissions must have an associated cost that

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reflects the toll they take on people and the environment. A price on carbon encourages individuals, innovators and investors to seek alternatives, such as solar and wind power, that do not cause carbon pollution. When economist Hoesung Lee became the new head of the Intergovernmental Panel on Climate Change in 2015, he named carbon pricing as the world's top climate change priority.

Several countries and regions have implemented carbon prices. In British Columbia, a carbon tax has helped cut fuel consumption and carbon emissions without harming economic growth. To prevent taxes from rising overall, the government also lowered personal and corporate income taxes; the province now has the lowest personal income tax rate and one of the lowest corporate tax rates in Canada.

Another way to remedy the market failure of pollution is to create a trading system where people can buy the right to pollute—a right that they can use, save or sell. A company that can reduce its emissions more than the law requires can sell any unused credits, whereas a company that cannot meet the standards can buy credits until it figures out how to solve its pollution problem.

The idea of being able to buy the right to pollute offends many people, but properly implemented, emissions trading can work. In 1990 Congress passed, by a wide margin, a set of amendments to the Clean Air Act that implemented trading in sulfur dioxide emissions to reduce acid rain. The program was highly successful: over the ensuing decade emissions were cut by more than 50 percent. In 1993 California followed this example and implemented the Regional Clean Air Incentives Market to reduce air pollution in southern California. The air in Los Angeles is far cleaner today than it was 30 years ago, but hardly anyone knows that this was achieved to a substantial degree through emissions trading. In 2015 China announced a plan to implement an emissions-trading system and has promised implementation by the end of 2020.

The essential idea behind both emissions trading or carbon taxes is to harness the power of market forces. Many business leaders prefer emissions trading over taxation because once the system is in place, it enables a good deal of freedom and flexibility. But the key phrase here is "once in place." An emissions-trading system, or a tax, has to be created, and that does not happen by the "invisible hand" of the marketplace. It happens through government action. Which brings us back to the role of government and the aim of the U.N. Conference of the Parties talks.

APPROPRIATE FORMS OF GOVERNMENT AUTHORITY ARE ESSENTIAL TO THE GUARANTEE OF LIBERTY. AS DISRUPTIVE CLIMATE CHANGE UNFOLDS, THEY WILL ALSO BE ESSENTIAL TO THE GUARANTEE OF LIFE AND THE PURSUIT OF HAPPINESS.

TECHNOLOGIES WAIT FOR SCALE

SOME PEOPLE, pointing to the recent rapid drop in the cost of solar power, argue that the market is responding and thus proves that we can solve climate change without Paris, without a big international treaty or even without government intervention at all. Others say that if we just implement a carbon tax, the market will do the rest. Neither position captures the whole story.

To stop climate change, we need a new energy system. This means large-scale renewable power, coupled with dramatic increases in three other factors: energy efficiency, demand management and energy storage. Solar and wind power work and in many domains are now cost-competitive, but they are not at the scale needed to replace enough fossil-fuel power plants to stop the ongoing rise in atmospheric CO_2 levels. After half a century of heavy and sustained public investment, nuclear power remains costly and controversial, and we still lack an accepted means of nuclear waste disposal. Carbon capture and storage—which collects emissions and puts them underground—is a great idea but has yet to be implemented.

A price on carbon will push demand in the right direction, but it needs to be reinforced by the pull of public investment in innovation. The most likely way we will get the innovation we need, at the scale we need, in the time frame we need and at a retail price that people can afford, is if the public sector plays a significant role.

It is possible that the market will bring us a technological breakthrough on climate change. But history suggests that this would be a long shot—even with a hefty price on carbon—because not one of the major technological developments of the 20th century was produced by the private sector working alone. Entrepreneurs such as Thomas Edison and George Westinghouse developed electricity, but it took the federal government to build the delivery systems that brought it to the lion's share of Americans. The same is true of telephone service. The federal government, starting with President Dwight Eisenhower, was needed to build an interstate highway system. Nuclear power was not a response to market demand: the U.S. government wanted to prove that the destructive power unleashed at Hiroshima and Nagasaki could have a constructive use. The U.S. military invented the Internet, as a technology under the Defense Advanced Research Projects Agency.

Former vice president Al Gore helped draft and pass the legislation that eventually released the Internet as a civilian technology that the private sector could commercialize and sell to millions of customers. The federal government developed digital computers, satellite communications, weather forecasting and the global positioning systems that tell mobile phones where we are. These transformative technologies were all created as public-private partnerships, more often than not with the government as lead partner. And they all took sustained effort over decades, the kind of effort for which the private sector has little stomach. A government pull is needed to develop climate solutions that, like the Internet, can be further advanced and marketed by the private sector. ARPA-E (Energy), an agency modeled after DARPA, is funding research in these areas, but its budget is peanuts. Its 2017 fiscal year request was $350 million. For comparison: in 2015 the world spent about $5.3 *trillion* in fossil-fuel subsidies and external costs, according to the International Monetary Fund.

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Carbon capture and storage requires special attention. The emissions-reduction goals being promised by many countries assume that these nations will be capturing carbon and storing it in the ground. But a proven system of long-term storage does not exist, not to mention a cost-effective one.

Technology exists to capture carbon dioxide (or any fluid) and pump it into geologic reservoirs: the oil industry already pumps CO_2 underground to help push oil out. But using CO_2 to flush a reservoir is very different than securely locking away that carbon for centuries or millennia. If carbon capture could be made feasible and economic, even at a moderate scale, it could greatly enhance emissions reductions. So we should invest in research—in geology, geophysics, hydrology and engineering—a domain in which our federal government has a long and strong track record. Many other countries have substantial expertise in these disciplines as well.

RECLAIMING THE COMMON GOOD

A HEFTY PRICE on carbon, coupled with major investments in technology, can definitely limit climate change. But both steps require government action. That suggests one other necessary step: we need to stop demonizing government and recognize its crucial role in doing the most important thing that markets do not do, which is prioritizing and sustaining the common good.

For the past 40 years the ideology of the unfettered marketplace has so dominated our discourse that most of us can scarcely imagine an alternative way of organizing our affairs. Individuals who try are dismissed as unrealistic, romantic, polemical or (in America) communists. When environmentalist and writer Bill McKibben suggested that a zero-growth economy could provide good lives for people while greatly reducing demand for the earth's dwindling resources, he was mocked. When Pope Francis released his encyclical on climate change and inequality, in which he urged the world to take on the interdependent challenges of caring for the planet and caring for the poor, critics all but accused him of being a socialist or "out of touch."

The pope is very much in touch with one essential fact: markets are effective in distributing goods and services efficiently to those who have the money to pay for them, but the needs of the poor go largely unaddressed, and the external costs remain almost entirely unpaid. Our dominant discourse insists that we can solve these problems by continuing the policies and practices that created them. The pope also noted that blind faith in the marketplace leads people to believe that they are free "as long as they have the supposed freedom to consume." So if the government acts to restrict the marketplace, it is (allegedly) restricting our freedom. But there are many different kinds of freedom, and as philosopher Isaiah Berlin noted many years ago, freedom for wolves can lead to the death of lambs, and surely the right to exist is more fundamental than the right to consume.

To build a better world, we first have to seek it. This requires a different vision, one that embraces priorities other than profit and places care—for creation and for one another—at its center. We have to accept the reality that markets are not motivated by the priority of care. And they are certainly not magical.

RETHINKING THE MAGIC OF THE MARKETPLACE

ECONOMIST NICHOLAS STERN and others have made the same point in more prosaic language. Investment in scientific research, public education and infrastructure is a common good, but our commitments to those activities have been weakened in recent decades. Yet history demonstrates that markets, by themselves, do not remedy market failures. Governments do.

In the aftermath of the cold war, conservatives and liberals agreed that market-based democracies had done a better job than centrally planned ones at providing goods and services, as well as protecting civil liberties and quality of life. But even Adam Smith, the champion of laissez-faire capitalism, noted that markets only function well with appropriate rules and regulations. One might have thought that the global financial crisis of 2008, the worst since the Depression, would have reminded us of the need for a reasonable set of rules. Instead we have continued to insist on the "magic of the marketplace," while decades of deregulated capitalism have led to environmental damage on a scale that threatens the very prosperity it is meant to generate.

We need a new conversation about the appropriate role of government in fostering innovation, remedying market failure and tackling inequality. We have to abandon magical thinking and quasi-religious faith in the marketplace. We must acknowledge that we need governance to foster the technologies needed to meet our energy demands without destroying the natural world.

Government is not *the* solution, but it has to be part of the solution. Although international agreements are useful in encouraging national governments to do the right thing, ultimately nations act on a national level. If the 20th century is any guide, once the government lays the foundations for new technologies, the private sector will step in to do what it does best, which is not to invent them but to sell them.

Above all, we have to reject the canard that addressing climate change threatens our liberty. Timothy Snyder—a foremost expert on the history of European fascism—reminds us that "a common American error is to believe that freedom is the absence of state authority." History shows that although state authority can be abused, its absence does not lead to liberty. On the contrary, its absence may open the door to tyranny and tragedy. Appropriate forms of authority are essential to the guarantee of liberty. As disruptive climate change unfolds, they will also be essential to the guarantee of life and the pursuit of happiness. SA

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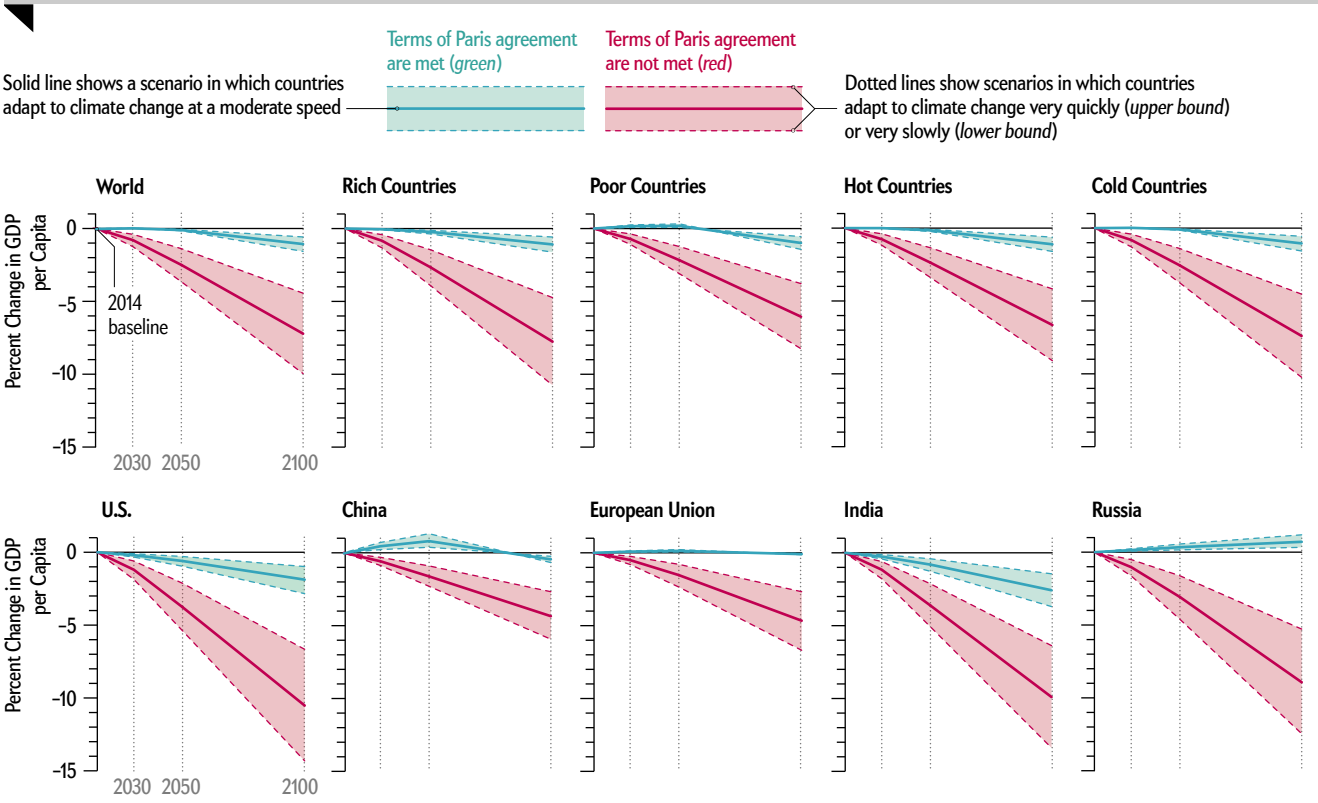

The Price of Warming

Countries rich and poor will take a financial hit

By Andrea Thompson

When a major heat wave engulfed western Europe in summer 2019, Paris and other cities recorded their highest temperatures ever. The furnacelike weather killed hundreds of people, and it exacted a financial toll in infrastructure damage, lost labor productivity and potentially lower agricultural yields. The situation illustrates how even relatively wealthy countries can take an economic blow from climate change.

That is a key message of a recent study from the nonprofit National Bureau of Economic Research (NBER). Earlier research has suggested that climate-related losses would be higher for poorer, hotter countries and that colder countries could even see economic benefits from warming. But this analysis indicates financial suffering will be widespread. "It doesn't matter what kind of country you are, you are going to get hit by climate change," says study co-author Kamiar Mohaddes of the University of Cambridge.

In a preliminary report for NBER, Mohaddes and other economists compiled per capita gross domestic product (GDP) and temperature data for 174 countries going back to 1960 to capture how above-normal temperatures have impacted income levels historically. They then projected that relation into the future to see how further warming could affect GDP, a measure of all the goods and services a country produces.

If greenhouse gas emissions continued to grow along their current trajectory, about 7 percent of global GDP would be lost by 2100, the researchers found. Rich and poor countries, as well as those with hot and cold climates, would all see GDP losses (*graphic*). The U.S. would lose 10.5 percent of its GDP, whereas Canada—which some economists say could benefit from warming because of expanded agriculture—would lose 13 percent.

Limiting emissions in accordance with the Paris climate agreement (which aims to keep global temperature rise below two degrees Celsius by 2100) would substantially stem the losses. Globally, the decline in GDP would be a mere 1 percent; in the U.S. and Canada, it would about 2 percent.

Unlike earlier studies, this one looked not just at temperatures but at how they deviate from the normal conditions to which societies have adapted. Although rich countries such as the U.S. may have more resources to compensate for swings away from those norms, the study results make clear that adaptation alone will not prevent major losses, Mohaddes says. "All of the infrastructure and the technology that we have mitigates the cost but cannot conceal it fully," says World Bank economist Stéphane Hallegatte, who was not involved with the study.

Both Mohaddes and Hallegatte say the projections most likely underestimate GDP losses because the study does not take into account the bigger variations in climate extremes expected in the future. SA

Andrea Thompson, an associate editor at *Scientific American,* covers sustainability.

SOURCE: "LONG-TERM MACROECONOMIC EFFECTS OF CLIMATE CHANGE: A CROSS-COUNTRY ANALYSIS," BY MATTHEW E. KAHN ET AL. NATIONAL BUREAU OF ECONOMIC RESEARCH, AUGUST 2019

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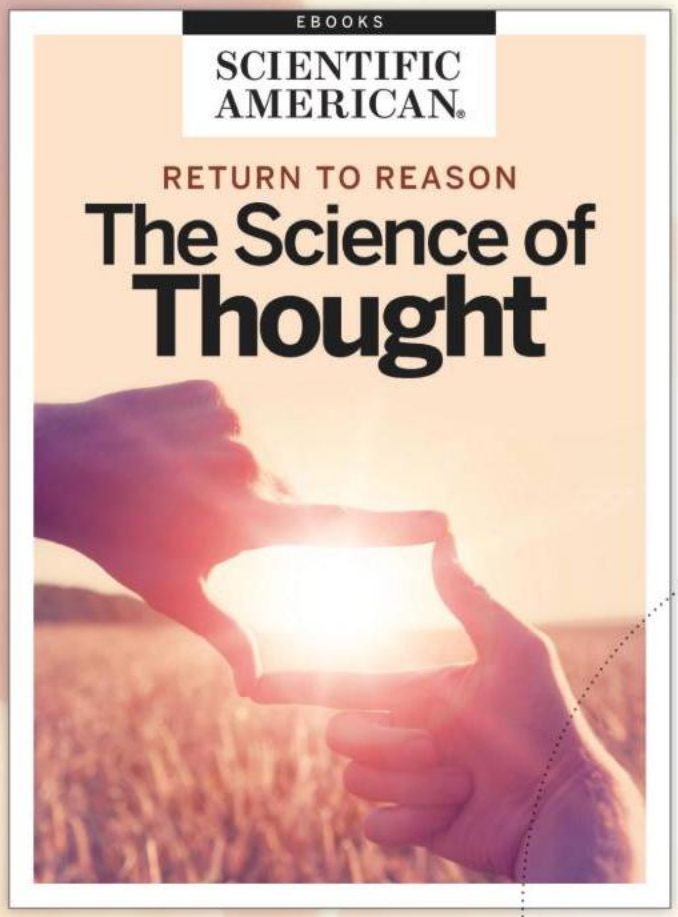

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